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Editorial Board

Зміст/Contents

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Use of the electrohydraulic effect as a means of intensifying the technological processes of oil collection and preparation

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Abstract. Unlike many other industries, where the electrohydraulic effect is widely used, its potential is practically not used in oil production. However, this phenomenon allows for the efficient conversion of electrical energy into mechanical energy and can contribute to the intensification of oil production processes. The aim of the study was to analyse the use of the electrohydraulic effect in industry, develop an electrical circuit for its implementation in the laboratory, and assess the possibilities of using this circuit to intensify oil production and treatment processes. For this purpose, the available literature on the electrohydraulic effect in other industries was analysed. A schematic diagram of a laboratory setup has been developed that will allow studying the effect directly on oil samples and oil emulsions. The created electrical circuit consists of elements that allow processing various liquid media, including formation water, oil emulsions and oil itself. The key advantages of using this circuit are high efficiency, powerful intensity of action, environmental friendliness, and the ability to adjust the intensity of the process. Widespread practical application of study results will help improve the efficiency and environmental safety of processes in the oil industry; thus, revealing the potential of this effect will be a significant step forward in the technologies of collecting, preparation and intensification of production of high-viscosity oils. This will reduce the cost of oil production, improve the quality of commercial oil, reduce oil losses with stable oil emulsions, and increase production. The results of this study will form the practical basis for the development of optimal technologies for the treatment of various types of heavy oils using the electrohydraulic effect

Keywords: technology; high-viscosity oil; electrical circuit; viscosity; oil emulsion

Introduction

The analysis of the state and problems of the technology of collection and preparation of oils and oil emulsions with abnormally viscous, non-specific properties shows that these technological processes require comprehensive research and intensification. These problems are mainly related to abnormal, non-standard, different physico-chemical properties of well products, such as density, viscosity, pourpoint, the presence of resins and asphaltenes, the content of paraffins and accompanying formation waters, etc. At the same time, the environmental component of production is also important, as the state of technology for the collection and processing of such abnormally viscous oils and oil emulsions can have a significant impact on the technogenic load in oil production areas. Solving these problems requires the use of similar non-standard solutions for intensifying production processes. One of the

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ways of significant intensification of technological processes of collection and treatment of mainly high-viscosity oil emulsions can be the technology of action using the electrohydraulic effect (EHE).

The EHE is used in various technological processes. For example, Q. Yu *et al*. (2022) investigated the effect of pulsed electrohydraulic shock used in the stimulation of hydrocarbon production on the parameters of a production well. The authors emphasised the main advantages of this method of action compared to others: significant energy capacity, the ability to remotely control the intensity and frequency of the action, environmental friendliness, etc. S. Chushchak *et al*. (2023) theoretically substantiated the use of electrohydraulic action to increase the efficiency of disintegration of tungsten pseudoalloys into microcomponents. In the work by A.G. Naryzhnyj (2019), the technology of using the EHE for deformation of a metallic cylindrical shell has been described. Researchers V. Matviychuk *et al*. (2020) described the application of the EHE in the agro-industry, where the classical scheme of the developed effect is used; equipment parameters and scope of application are given. In their research, V. Popescu *et al*. (2019) also justified the development of an electrohydraulic scheme for processing agricultural products. V. Baranov *et al*. (2022) suggested using the electrohydraulic method for promising methods of obtaining organic fertilisers. In the work by V. Bereka & I. Kondratenko (2021), the use of the EHE for water purification and disinfection has been justified, and in the article by A. Turdiboyev *et al*. (2023), the EHE has been used to disinfect the water environment and feed plants. N. Markaev *et al.* (2023) also substantiated the use of EHE for intensification of plant growth. The paper by J.V. Sabrejos *et al*. (2020) showed the design parameters of the hydraulic installation and simulated the factors influencing the process of electrohydraulic water treatment.

Basically, all the mentioned works relate to the use of EHE in various industries. In the oil industry, this effect was hardly used, and research on the intensification of the processes of preparation of abnormally viscous oils and oil emulsions, as well as associated formation waters using the EHE, is devoted to a small number of works, which indicates insufficient study of the effective action of this effect and the conditions of its application. The above-mentioned well-known and quoted works, such as Q. Yu *et al.* (2022), did not provide reasonable electrical schemes for the realisation of this effect. Experimentally, V. Bychkov & A. Ivanov (2019) established that it is possible to deliberately distribute the energy properties of discharges in series-connected three-electrode systems. This finding expands the technological possibilities for processing materials in discharge chambers with complex geometry. There are practically no laboratory facilities, the different modes of operation of the facilities are not studied, and there are no characteristics of the necessary equipment, etc. This work requires extensive consideration, justification and research. The purpose of this study was to justify the use of EHE in the production and preparation of high-viscosity oil. This required an analysis and comparison of the way this effect is used in other industries, as well as the creation of a basic electrical scheme for implementing this effect in laboratory conditions.

Materials and Methods

A comprehensive analysis and integral summary of a significant mass of scientific and technical literature was carried out; a large number of literary sources, including monographs, articles in leading scientific publications, materials from conferences devoted to the use of EHE in various industries were analysed. Most of these sources refer to the initial period of the discovery of this effect by L. Yutkin in the period from 1950 to 1989. This analysis made it possible to identify modern trends and gaps in research and to formulate concrete tasks for the application of this effect in the oil industry. More than 238 patents were searched, leading technical solutions, structural features, parameters, trends in the development of technologies using EHE were analysed in detail, which allowed to theoretically substantiate the optimal parameters for specific conditions of its application (Google patents, n.d.). The main patent base for the analysis were the developments and official patents developed by L. Yutkin as the founder of this field of research.

An analysis of existing problems in the extraction of abnormally viscous oils and oil emulsions was carried out. Based on the theoretical analysis of the physico-chemical properties of oils, oil emulsions and accompanying waters with different physico-chemical characteristics, the analysis of regulatory and technical documentation, a wide array of patent information, the use of the EHE in the collection and preparation of oil is substantiated. An analysis of the sources of existing methods of extracting high-viscosity oils and technologies of wave action on them was also carried out. In the course of this research, a thorough comparative analysis of existing technologies and various methods and approaches to the creation and practical application of the EHE in scientific research and industry was carried out. The methodological basis of the study was a detailed study and critical analysis of the results of previous studies of this issue already available in the scientific literature. Scientific methods were comprehensively applied in the research, a comprehensive analysis of literature, patents and technical solutions was carried out in order to deeply study the possibilities and positive aspects of using the EHE.

An in-depth analysis of the physical processes that can occur during the application of EHE allowed the development and theoretical substantiation of the optimal parameters and regimes of the electrical circuit for specific conditions and applications. The main principles of the development of this electrical scheme were that the scheme should fully ensure the given functionality and work reliably and stably in the entire possible range of operating modes and operating conditions, taking into account limit and transient processes. It must be as simple as possible, logically and rationally constructed, and use the optimum element base from the point of view of the price/quality ratio in order to reliably achieve all the necessary technical parameters, characteristics and requirements. In addition, the developed scheme shall include reliable and comprehensive means of protection against the possible harmful effects of interference, current and voltage overloads, short circuits and other emergency and undesirable situations that may lead to damage or failure.

Results

The production of classic abnormally viscous oils and oil emulsions is insignificant in Ukraine. Such oils are produced in the Kokhanivske, Bugrivativske, Orkhovytske and Yablunivske fields. The almost insignificant production of such oils from these deposits is due to industrial and production difficulties, increased costs, problems with oil collecting and preparing, etc. Taking into account the properties of oils under standard conditions, according to international practice, hard-to-recover oils and oil emulsions also include oils with a high pour point due to high paraffin content; therefore, the share of such oils is much higher. As an example, such oils can be mentioned as oils from the Verkhnemaslovetske field with a pour point of +16 °C, Novoskhidnetske (+14 °C), Zavodivske (+20 °C), Oryv-Ulychnianske (+20 °C) and others. To minimise these costs and increase production at such fields, it is necessary to introduce new methods and technologies to intensify all technological processes from the well to the finished product. One of these new, innovative methods can be the method of acting on oil and oil emulsions using the EHE.

EHE is based on a hitherto unknown phenomenon, which consists in a sharp increase in the hydraulic and hydrodynamic effect, as well as the amplitude of the shock wave, when a pulsed electrical discharge is created in a liquid. In order to obtain the maximum effect, it is necessary to reduce the duration of the pulse to a minimum in order to ensure the possible leading edge of the pulse and its shape close to the aperiodic one. EHE was discovered in 1953 by L. Yutkin (1955). In spite of numerous discussions about this phenomenon, the effect is widely used in many industries to develop advanced technologies. L. Yutkin made a significant contribution to the research and implementation of EHE and was awarded around 200 patents (Electrohydraulic effect..., n.d.). The researcher's work helped to realise the potential of this discovery in practice. As of 2024, the figure of L. Yutkin and his achievements are undeservedly forgotten. Effective implementation of EHE in industry requires thorough laboratory research and feasibility studies. It is important to record all the results of such work for further analysis and improvement of technologies based on this effect. As L. Yutkin (1986) stated, the essence of this method is that when a specially formed pulsed electric discharge (spark, brush and other forms) is carried out inside a volume of liquid located in an open or closed vessel, ultra-high hydraulic pressures arise around the zone of its action, capable of performing useful mechanical work and accompanied by a complex of physical and chemical phenomena.

The mechanical effect of the fluid on the objects located near the discharge channel according to the basic scheme shown in Figure 1 is extremely small for fluids with ionic conductivity (formation water) and comparatively larger for fluids with dielectric properties (oil). The mechanical effect is due to the pressure inside the vapour-gas bubble in the discharge zone. According to V. Matviychuk *et al.* (2020), these values are insignificant and do not have a significant effect on the fluid.

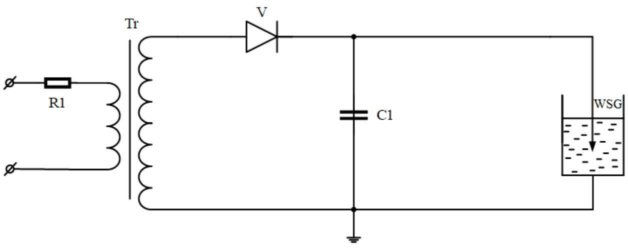

Figure 1. The basic electrical scheme of electric discharge technology

Note: R1 – charging resistance; Tr – transformer; C1 – capacitor, working capacity; V – rectifier; WSG – working and spark gap in the liquid

Source: created by the authors based on L. Yutkin (1955)

According to the scheme shown in Figure 1, L. Yutkin (1986) proposed schemes (Fig. 2; Fig. 3) that made it possible to significantly increase the intensity of the mechanical action of the discharge on the liquid and which differ in that they contain an air spark gap that forms the discharge.

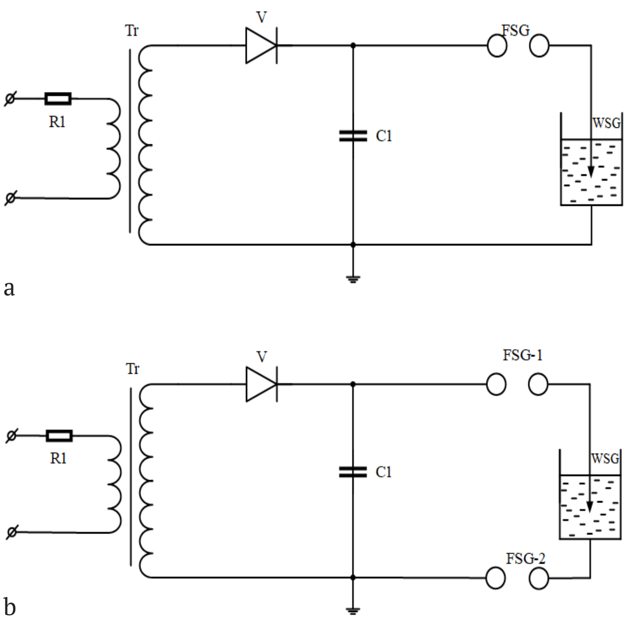

Figure 2. Schematic diagram of the EHE

Note: a – schematic diagram of the EHE with one forming spark gap (FSG); b – schematic diagram of the EHE with two FSGs

Source: created by the authors based on L. Yutkin (1986)

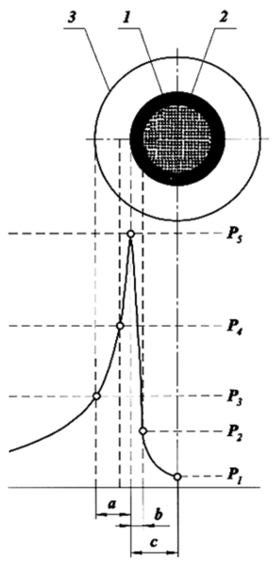

Figure 3. Schematic diagram of the discharge channel structure and pressure distribution

Note: 1 – the central part of the discharge channel; 2 – "skin" shell of the channel; 3 – vapor-gas shell; *a* – thickness of the vapour-gas shell, $a \approx 0.001...0.1$ mm; *b* – thickness of the "skin" shell, $b \approx 10^{-5}...10^{-3}$ mm; *c* – radius of the discharge channel, $c \approx 0.5... 5$ mm; $P_1...P_5$ – pressures in the corresponding zones, $P_1 = 0...2 \times 10^6$ Pa, $P_2 \leqslant 2 \times 10^8$ Pa, $P_3 \leqslant 5 \times 10^9$ Pa, $P_4 \leqslant 2 \times 10^{10}$ Pa, $P_5 \leqslant 10 \times 10^{10}$ Pa

Source: created by the authors based on L. Yutkin (1986)

L. Yutkin (1986) defined three main operating modes of operation of the plant: hard – V > 50 kV; C < 0.1 μF; medium – 20 kV < V < 50 kV; 0.1 μF < C < 1.0 μF; soft – V < 20 kV, C > 1.0 μF. According to L. Yutkin (1986), FSGs provide an opportunity: to accumulate the necessary amount of energy with a pulse supply for the main gap of the discharge; to significantly reduce the pulse time and regulate its frequency and intensity; to create a steep pulse front preventing the transition to an arc discharge; to obtain the required current and voltage at a given main gap; to create the required shape and character of the pulse. The implementation of the EHE is characterised by the mode of energy release at the active resistance of the circuit close to the critical one, according to the formula:

$$1/C < R^2/4 \times L, \quad (1)$$

where *C* is a capacitor capacity; *R* is an active resistance of the circuit; *L* is an inductive resistance of the circuit. The main idea is that due to the special parameters of the electric pulse in the fluid, there is a sharp increase in hydraulic and impact effects, which was previously an unknown phenomenon. According to the formula, the key factors influencing the occurrence of EHE are the amplitude, the slope of the front, the shape and the duration of the electric current pulse.

The duration of the current pulse, measured in microseconds, allows the instantaneous power of the pulse to reach hundreds of thousands of kilowatts. The steepness of the pulse front determines how quickly the discharge channel expands. At voltages of several tens of kilovolts, the current amplitude of the pulse reaches tens of thousands of amperes, resulting in a sharp increase in fluid pressure. This sudden increase in pressure results from the instantaneous release of a significant amount of energy within a confined volume of liquid. The implementation of EHE is associated with a relatively slow accumulation of energy in the power source and its almost instantaneous release into the liquid medium. The energy is gradually accumulated and then suddenly released, creating an EHE.

The main factors of EHE are ultra-high impulse hydraulic pressures (Fig. 3), which cause shock waves with supersonic speed; significant impulse movements of liquid at a speed of hundreds of metres per second; powerful cavitation processes; infrared and ultrasonic radiation; mechanical resonance phenomena; strong electromagnetic fields; intense light, heat, ultraviolet and X-ray radiation; pulsed gamma and neutron radiation; multiple ionisations of substances. All these factors together create a powerful, complex effect on the liquid and the objects in it. Due to these factors, EHE is able to perform a wide range of physical and chemical actions. For example, shock waves can destroy solid structures, and cavitation processes can disperse solid particles.

The main advantages of using EHE include: high intensity of action; the possibility of simple intensity adjustment; a relatively simple scheme with the use of standard elements; environmental friendliness; and high efficiency. The EHE is of great practical importance and is used in various fields, from mining to medicine. Due to the unique capabilities of this physical phenomenon, EHE allows solving complex technical and technological problems. Research on EHE is still ongoing, as this effect still holds significant potential for the development of science and technology. Powerful shock waves arising during the development and sudden collapse of cavitation cavities can destroy non-metallic materials and cause plastic deformations of metallic objects located near the discharge zone. Intense infra- and high-frequency ultrasonic vibrations accompanying the electro-hydraulic effect during the discharge additionally grind materials already split into pieces, cause resonant destruction of large solid objects into separate small crystalline particles, and intensify the fast-moving chemical processes of synthesis, polymerisation, and breaking of sorption and strong chemical bonds between molecules.

The strong electromagnetic fields generated during electrical discharge also have a significant impact on both the discharge process itself and the ionic processes occurring in the liquid around the discharge channel. Under the influence of these electromagnetic fields, a variety of transient physical and chemical changes can occur in the processed material and the surrounding liquid. The form of electrical discharge, which causes the generation of powerful impulse shock waves and pressures, can be very diverse – from a spark discharge to a discharge in the form of a long brush, as well as in the form of a continuous flow without a clear structure (the so-called impulse electric wind). The use of the method of generating ultra-long spark discharges directly in liquid media is the basis that provides wide technological possibilities of the EHE and its application for processing various materials. However, the EHE and related phenomena can also be obtained as a result of another physical process, the so-called "thermal explosion", when instead of a spark electric discharge, rapid heating and explosive vaporisation of a thin conductive element connecting electrodes placed in liquid The use of this method makes it possible to expand the fields of application of phenomena related to the EHE to high-temperature liquid and gaseous media, including melts of metals and salts, as well as plasma.

The environmental friendliness of processing materials by means of EHE should be emphasised, as the physical principle of this method does not introduce any harmful impurities or additional sources of pollution into the processed environment. The electro-hydraulic influence is based solely on the use of electrical energy and the properties of the medium itself. EHE can be effectively used in chemical technologies to intensify processes. As a method of mechanical, physical and chemical action on materials, it can be used for polymerisation, depolymerisation, synthesis of chemical compounds, increasing the activity of catalysts and accelerating the speed of reactions in the chemical industry.

Studies of the effects of waves and pulses on oil and gas formations have been carried out in the past but have not been widely used. Recently, attention to such methods has increased in connection with the development of technologies and the search for new effective approaches to the extraction of hard-to-reach hydrocarbon reserves. Abroad, considerable success has been achieved in the production of high-viscosity oil using new specialised equipment such as long-stroke rod pumps, screw pumps and hydraulically driven centrifugal pumps. This allows more efficient production of complex, high-viscosity hydrocarbon reservoirs.

A promising direction is the complex combination of various physicochemical methods for the integrated impact on the productive layer and the maximum increase in the efficiency of extraction of hard-to-reach hydrocarbon reserves. Each of the methods correctly selected for specific geological and technological conditions will achieve a positive result. A group of technologies based on various wave and resonance processes and chemical or thermal effects can be considered promising for the development of hard-to-extract reserves. To study the effect of EHE on oil-water mixtures, a scheme for conducting laboratory studies was developed (Fig. 4).

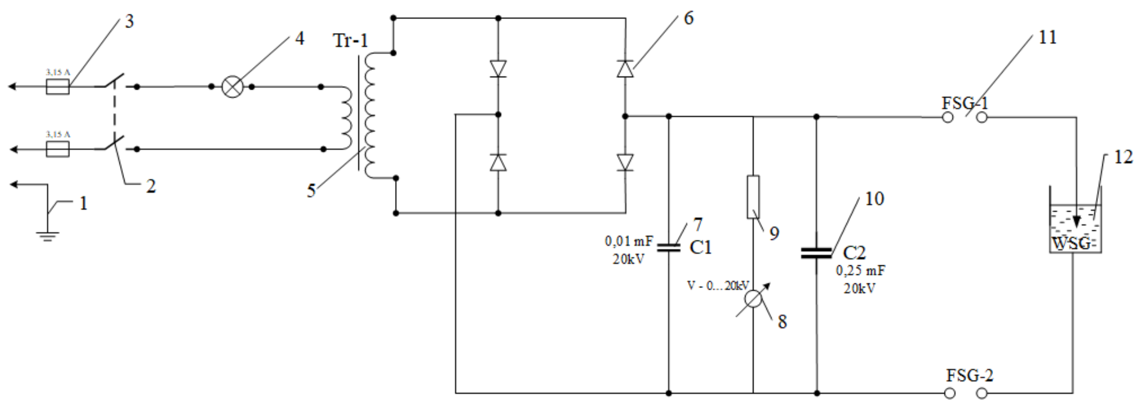

Figure 4. Developed schematic electrical diagram of the EHE study

Note: 1 – grounding; 2 – switch; 3 – fuse; 4 – lamp; 5 – transformer; 6 – diode; 7 – capacitor; 8 – voltage regulator; 9 – resistor; 10 – working capacitor; 11 – air spark gap; 12 – WSG forming spark gap in the working capacity

Source: created by the authors

The main advantages of using this scheme are high efficiency, high intensity of action, environmental friendliness, ability to regulate the intensity of the process, etc. The aim is to reduce the cost of oil production, improve the quality of commercial oil, minimise oil losses by maintaining stable oil emulsions and ultimately increase production rates. As known from L. Yutkin (1955), the efficiency of EHE is significant. It should be noted that, according to the scheme developed, the intensity of the effect can be regulated by changing the charging rate of the capacitors, which makes it possible to process emulsions at three different charging rates. The intensity of the effect can also be adjusted by choosing the distance between the air gaps and the capacitance of the capacitors. The use of this effect will make it possible to reduce or even eliminate the use of chemicals in the destruction of stable emulsions. The developed scheme will allow the medium to be processed at medium speed and can be used in both industrial and laboratory conditions. The high efficiency of EHE and the unique possibilities of electrohydraulic action are the basis for the wide use of EHE in all fields of science and technology.

Discussion

According to the analysis of the existing literature, the use of EHE for the preparation and extraction of heavy oil was practically not carried out. At the same time, EHE is used in other industries due to its versatility. For example, A.G. Naryzhnyj (2019) considered a mathematical model of thermomechanical processes in a technological system of free dispensing of a thin-walled shell under the influence of the EHE. The model included: vapour-plasma channel that expands as a result of the release of a heat pulse, a process fluid that transmits hydraulic action, equipment that directs the movement of the fluid and a technological object in the form of a thin-walled deformable elastic-plastic shell. The model was used to study the processes of EHE action on a thin-walled shell in specific technological schemes, which were used for experimental studies and their comparison.

Since its discovery, the EHE has been mainly used to deform metals. V. Zagoruyko (2019) emphasised that one of the distinctive features of high-energy metal processing methods is the ability to stamp hard-to-deform metals and alloys. In addition, such methods ensure the manufacture of parts with high dimensional and shape accuracy. An important factor is the uniform load distribution over the entire surface of the workpiece during deformation. This ensures that the relative velocities of the workpiece particles are below critical values and eliminates the possibility of metal fracture. V. Sirenko & O. Manchenko (2020) substantiated that the use of electrical energy – a high-potential and environmentally friendly form of energy – contributes to the implementation of technological processes with high intensity and minimal emissions. The direct interaction of electric and magnetic fields and their effect on food raw materials is particularly effective in the processing of agricultural products. The main feature of these processes is the direct conversion of electrical energy into mechanical action. However, the duration of this action cannot be too long due to the significant thermal effects that occur.

N. Markaev *et al*. (2023) investigated the effect of EHE on the aquatic environment and considered possible options for electrical schemes. The article by A. Turdiboyev *et al*. (2023) described the use of the EHE for wastewater decontamination and increasing the nutrient content in water. They emphasised that EHE is characterised by low energy consumption, short processing time, simplicity of equipment, and environmental friendliness. The developed circuit contained a laboratory autotransformer, high-voltage diodes, a high-voltage capacitor bank K75-15, and an FP-emission gap for voltage regulation. J.V. Sabrejos *et al*. (2020) also studied the technology and technical means of electrohydraulic action on water. The authors developed the shape of the electrode tip to increase the electromagnetic field density and reduce power losses. The paper specified the parameters of the electrohydraulic plant, modelled the factors affecting the process of electrohydraulic water treatment, optimised the operating modes of the electrohydraulic plant, and conducted a feasibility study. The work of T. Golubeva *et al*. (2018) presented the experimental laboratory equipment developed by the authors, which enables the use of a pulsed electric discharge using the EHE. This experimental equipment can be used to treat wastewater from thermal power plants, oil refineries, and other polluting industrial enterprises. The work investigated the environmental effects of the developed equipment on the example of water contaminated with phenols and oil products, which is purified by destroying molecular and ionic bonds with free electrons and ions that appear during the discharge.

The effect of EHE use during reservoir treatment can significantly intensify and increase the production of heavy oil. Research by I. Denysiuk *et al*. (2019) showed that the oscillating movement of a viscous fluid in the pore channels of an oil reservoir is accompanied by waves of compression and rarefaction. These waves create a dynamic effect on the pore channels and initiate directionally variable filtration flows. The analysis of velocity profiles along the cross section of the pore channels revealed that during the harmonic action, reverse oscillatory flows occur inside the pores. There is also an increase in fluid velocity near the walls of the pore channels compared to regions near the axis of the channel. According to the results of numerical calculations of the volumes of fluid filtered through the pore channels of the formation during wave treatment and the analysis of literary sources, it is recommended to use the combined effect of several methods, for example, a combination of wave and chemical treatment. The basic idea is that the oscillatory movement of the fluid in the pore channels creates compression/discharge waves that initiate alternating filtration flows, reverse flows, and an uneven velocity profile. To increase production efficiency, it is proposed to combine wave treatment with other methods, such as chemical treatment.

The technology for the intensification of oil production by means of wave technology is described in the work of Y. Yakymechko & S. Oveckiy (2023). This study described the technology and technical means for creating a shock wave impact on the bottomhole zone of a productive formation in the perforation interval. This allows to locally simulate the geodynamic impact on the formation in small volumes. Restoration of the potential productivity of production and injection wells is achieved by destroying colloidal dispersed systems that clog the bottomhole zone of the formation. This occurs as a result of wave impact, which restores the permeability and patency of the pore channels in this zone. Thus, a special technology is used with the use of technical equipment to generate shock waves and transmit them to the bottomhole zone of the well. This simulates the impact of natural geodynamic processes and allows the formation zone near the well to be cleaned of contaminants, restoring its productivity. A similar effect on the formation can be achieved using EHE.

More recent studies on the bottomhole treatment of reservoir zones carried out in Ukrainian fields include V. Zhekul *et al*. (2017). They presented a generalised analytical review of research and development carried out at the Institute of Pulse Processes and Technologies of the National Academy of Sciences of Ukraine from the end of the 1970s, regarding the creation of downhole electric discharge units for the intensification of mineral production. The features and advantages of such installations are: high power, selectivity and cyclicity of repeated impact on the treated object – the bottomhole zone of an oil and gas formation; the ability to regulate the main technological parameters; ease of operation; safety and environmental friendliness with a fairly high impact efficiency and relatively low costs for well treatment. The idea that the use of the EHE is not only efficient but also causes minimal environmental damage is confirmed by A. Satybaldin *et al*. (2021). In this paper, researchers considered the application of the EHE for the processing of oil sediments.

As can be seen from the above discussion, EHE is widely used in many industrial sectors: mechanical engineering – sheet metal stamping, cylindrical billet forming, calibration, pressing, strengthening, and removal of residual stress in structures; metallurgy – intensification of charge preparation processes, ingot crystallisation, flattening, drawing and pressing, destruction of metallurgical equipment lining during repair work, regeneration of lining materials mining and exploration – rock destruction, ore dressing; oil and gas – well drilling, cleaning of drilling equipment; construction – sinking of sheet piles, piles, pipes, soil compaction, development of frozen ground, preparation of mortars, etc. The number of studies investigating the application of this effect in the oil and gas industry is limited, yet highly promising.

Conclusions

Technological processes for the collection and preparation of oils with abnormal properties, such as high-viscosity, presence of resins, asphaltenes, paraffins, etc., require careful study and intensification due to their specific physical and chemical characteristics and the potential environmental impact of their production. The use of EHE can be a promising and effective way to intensify the processes of collection and preparation of high-viscosity oils and oil emulsions. However, despite its significant potential, the use of EHE in the oil industry is currently limited and existing research does not provide sufficient data and technical solutions for its practical implementation and introduction into production processes. The purpose of this study was achieved by summarising and analysing the available data on the use of the EHE in various industries, identifying possible technical solutions, developing a basic electrical circuit for the laboratory implementation of the effect, selecting the main components of the circuit and establishing its modes of operation for the intensification of oil production and preparation processes. In the framework of this research, a comprehensive approach was used, which involved the use of a wide range of both theoretical general scientific methods and empirical methods of scientific research. In particular, a thorough comparative analysis of existing technologies, various methods and approaches to the creation and practical application of the EHE in scientific research and industrial fields was carried out.

The circuit diagram developed within the framework of the study includes modern elements that allow processing various liquid media, such as produced water, oil emulsions, and oil. In the future, the developed scheme will be implemented and integrated into the scheme of laboratory testing of oils and oil emulsions. It is expected that the results of this study will allow to substantiate and develop effective technical means and to conduct laboratory studies on the use of EHE as a promising technology to improve the efficiency of operations with abnormal high-viscosity oils and emulsions, which will contribute to the improvement of their production and treatment processes.

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Conflict of Interest

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Використання електрогідравлічного ефекту як способу інтенсифікації технологічних процесів збору та підготовки нафт

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Анотація. На відміну від багатьох інших галузей промисловості, де електрогідравлічний ефект має широке застосування, у нафтовидобутку його потенціал практично не використовується. Проте саме це явище дозволяє ефективно перетворювати електричну енергію в механічну і може сприяти інтенсифікації процесів нафтовидобутку. Метою дослідження було здійснення аналізу використання електрогідравлічного ефекту в промисловості, розробка електричної схеми для його реалізації в лабораторних умовах та оцінка можливостей застосування цієї схеми для інтенсифікації процесів видобутку та підготовки нафти. Для цього було проведено аналіз доступних літературних даних щодо електрогідравлічного ефекту в інших галузях промисловості. Розроблено принципову електричну схему лабораторної установки, яка дозволить досліджувати ефект безпосередньо на зразках нафти та нафтових емульсіях. Створена електрична схема складається з елементів, які дають змогу обробляти різноманітні рідкі середовища, зокрема пластову воду, нафтові емульсії та саму нафту. Ключовими перевагами використання цієї схеми є високий коефіцієнт корисної дії, потужна інтенсивність дії, екологічність, а також можливість регулювати інтенсивність процесу. Широке практичне застосування результатів дослідження сприятиме підвищенню ефективності та екологічної безпеки процесів у нафтовидобувній галузі, таким чином, розкриття потенціалу цього ефекту стане значним кроком вперед у технологіях збору, підготовки та інтенсифікації видобутку високов'язких нафт. Це дасть можливість зменшити собівартість видобутку нафти, покращити якісні показники товарної нафти, зменшити втрати нафти зі стійкими нафтовими емульсіями, збільшити видобуток. Результати цих досліджень стануть практичною основою для розробки оптимальних технологій підготовки різних типів важких нафт із використанням електрогідравлічного ефекту

Ключові слова: технологія; високов'язка нафта; електрична схема; в'язкість; нафтова емульсія

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Development and research of the properties of sealing grease for threaded connections of casing pipes

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Abstract. The tightness of threaded connections in casing is a critical issue, as it directly affects the reliability of well casing and, consequently, their trouble-free and long-term operation. Given that the oil and gas industry is tasked with maximising the energy demand by its own production, this problem remains relevant. The aim of this study was to investigate the properties of a newly developed sealing grease for threaded connections in casing pipes and to confirm its effectiveness compared to other commercially available products. Analytical and experimental methods were used to conduct the research. Industrial material was analysed for the quality of well casing and it was revealed that numerous

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wells exhibited defects in their casing associated with the leaks of threaded connections of casing pipes. The causes of threaded connection failure were classified and the main factors affecting their tightness were identified. A sealing grease was developed, consisting of carbamide resin, organophilic aerosil, graphite, fumed silica and ammonium chloride. The following indicators were determined to evaluate the effectiveness of the developed grease: friction coefficient on the steel-steel surface, adhesion strength, grease shear resistance, tightness of the threaded connection during internal pressure testing, and coefficient of performance. It was established that the proposed grease has a higher initial adhesion force than others, and it also increases steadily during the polymerisation process and reaches its maximum value after fifteen hours of curing; the grease has a lower coefficient of friction, higher shear resistance and a significantly higher efficiency factor. The studies confirmed an increase in the performance of threaded connections of casing pipes using the developed lubricant

Keywords: well casing; efficiency coefficient; reliability; sealing grease; adhesion force

Introduction

The problem of ensuring the tightness of threaded connections in casing pipes was regarded as one of the most pressing issues in the oil and gas industry. Leakage of these connections caused significant economic losses due to accidents, complications during drilling and operation of wells, and also had a negative impact on the environment. The main aspects of the issue were justified by the following aspects: high frequency of complications and significant negative consequences; the complexity of ensuring reliable tightness; the influence of a wide range of operational factors; the imperfection of existing designs and technologies; economic and environmental components.

The wells under construction at present were considered highly expensive engineering and technical structures designed for long-term operation. However, during the construction process, complications and accidents occurred, caused by a decrease in the performance of casing strings due to the loss of initial strength and tightness of their coupling joints. According to researchers N. Ji *et al*. (2023) and B. Yang *et al*. (2023), improving the reliability of casing strings is a prerequisite for increasing the efficiency and ensuring the safety of the operation of oil and gas wells constructed in difficult mining conditions, which requires improving their technical parameters, and this primarily concerns the threaded connections of pipes used for these strings. Scientists H. Xu *et al*. (2023) and B. Kim & J.-Y. Yoon (2024) noted that most often, coupling threaded connections were used to complete casing in industrial environments, which are subject to requirements not only for strength for various types of loads, but also for tightness. The thread profiles used in casing connections are inherently leaky due to their structural features.

In some threaded connection designs, such as trapezoidal threaded casing with increased tightness (TTC) and couplingless casing (CC), provide for sealing elements on the contacting surfaces, which, when screwed together properly, form an impermeable contact. According to V. Vasylyshyn *et al*. (2020), the manufacture of such connections requires high accuracy, precision equipment, which affects the cost of casing, and in some cases, even such connections do not provide the necessary wellbore fixing functions. According to the results of the research by Z. Xu *et al*. (2023) note that leaky threaded connections can be a result of deviations in the geometric parameters of the thread from the requirements of the standard, namely: deviations in the profile of turns, pitch, taper and axial tension of the thread, which can lead to incomplete contact of surfaces and the formation of gaps. C. Blanc *et al*. (2019) argue that it is also important to avoid defects on the surface of the threads during threading (burrs, dents, scratches) and damage during transport.

Therefore, solving the problem of tightness of casing threaded joints will prevent interbedded cross flow, as casing strings are designed to isolate different geological horizons, thereby preventing uncontrolled movement of fluids (oil, gas, water) between them. Leaky joints can lead to contamination of productive formations, watering of wells, reduced production rates and loss of valuable resources. Tight casing joints ensure the integrity of the wellbore as they guarantee the strength and stability of the casing string under various types of loads (own weight, rock pressure, hydraulic pressure of liquids, temperature fluctuations).

Environmental protection, personnel and equipment safety are still important. Uncontrolled leakage of corrosive impurities that may be present in hydrocarbon fluids (hydrogen sulphide, carbon dioxide, sulphur) through leaky connections can lead to pollution of groundwater, soil and the atmosphere, causing significant damage to the ecosystem, and pose a threat to the life or health of personnel and damage to equipment. The aim of the study was to develop an effective sealing agent for threaded casing joints, to experimentally evaluate its properties, and to compare its main parameters with existing analogues. Based on the above, the following tasks were formulated to solve the problem of tightness of casing threaded joints: conducting analytical studies of leakage of casing threaded joints; identifying the main factors affecting such leakage; developing and substantiating the formulation of a sealing lubricant; determining its main properties; conducting experimental studies to assess the effectiveness of the lubricant compared to the analogues used.

Materials and Methods

The effectiveness of any sealing grease must be confirmed by the following requirements: maximum mobility, i.e. low viscosity, at the time of screwing the threaded connection to ensure that all gaps are filled with grease; minimum mobility (high viscosity) during the operation of threaded connections; increased operating pressure and temperature limits (respectively 50-70 MPa at 200°C) while maintaining operational characteristics; pronounced structural properties and ability to resist shear. Taking into account the above requirements, a sealing grease for casing threaded connections was developed by scientists from the Department of Oil and Gas Well Drilling of the Ivano-Frankivsk National Technical University of Oil and Gas (US-OT) (Kotskulych & Tyshchenko, 2009).

The sealing grease consists of a carbamide resin binder, ammonium chloride hardener, as well as an organophilic aerosil and fumed silica, with the following ingredient ratios, %: organophilic aerosil – 4-6; graphite – 5-8; fumed silica – 0.5-1.0; ammonium chloride – 1-2; carbamide resin – the rest. The US-OT sealing grease is prepared according to the following procedure. A fumed silica is added to the calculated mass of the organophilic aerosil and mixed until a homogeneous state is obtained. Then the resulting mixture is injected into carbamide resin, graphite is added and mixed for 20-30 minutes. Before use, the required amount of hardener is added to the composition and mixed until a homogeneous mass is obtained. The grease can be polymerised at temperatures above 100°C without the addition of a thickener. Apply the grease to the surface with a paint brush in a uniform layer.

The quality of the sealing grease was assessed by the following indicators: friction coefficient (affects the value of the screwing torque), adhesion force (characterises the strength of adhesion of the lubricant to metal thread surfaces), shear resistance of the lubricant (to assess the viscosity characteristics of the lubricant), tightness of the threaded connection (determines the resistance of the lubricant to extrusion from the thread gap under high pressure), and lubricant efficiency factor. Similar studies were conducted using USSA and R-2 MVP greases to compare the performance indicators. As of 2025, they are produced in accordance with GOST 3333-80 (1980) outside Ukraine. The manufacturer of these lubricants is Expert-oil. All of the above indicators were determined by the experimental method using the instruments available at the Department of Oil and Gas Well Drilling, except for the lubricant efficiency factor, which was estimated by the analytical method using experimental data. In order to analyse the technical condition of production and intermediate casing strings, there were considered cases of leakage at the fields of the Shebelynka Drilling Department (SDD), in particular, at such sites as Yulivske, Muratovske, Zakhidno-Shebelynske and Lychkivske.

The adhesion force was measured by the method of determining the force of separation of a metal disc that interacted with a metal plate through the lubricant after contact for one minute. The change in the adhesive properties of the lubricants over time was also measured. The coefficient of friction was measured using the PT-2 device. This device was developed at the Department of Oil and Gas Well Drilling at the Ivano-Frankivsk Institute of Oil and Gas on the basis of the widely used SNS-2 device in the 1980s. It was designed to determine the coefficient of friction of various materials. The shear resistance of the lubricant was assessed using the simplest method – forcing the lubricant through the holes in the container and matrix using the C-2 device (Fig. 1).

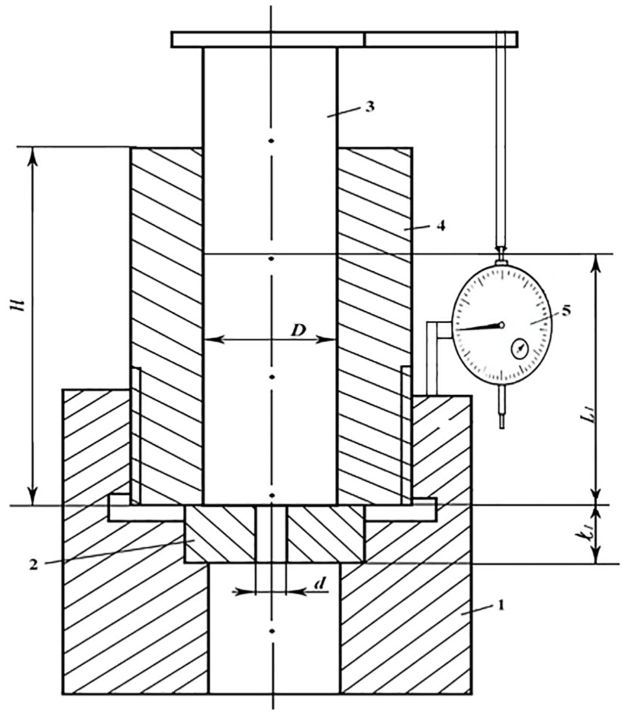

Figure 1. Device for determining the shear strength of grease

Note: 1 – body; 2 – matrix; 3 – punch; 4 – container; 5 – clock-type indicator; D – diameter of the container hole; d – diameter of the matrix hole; the thickness of the matrix is selected from the condition of filling the container with lubricant

Source: developed by the authors

The procedure for evaluating the shear resistance of the grease was as follows. The container of the device was filled with sealing grease, after which a compressive load was applied to the punch and the moment of grease pushing through the hole of the die was recorded according to the readings of the clock-type indicator. The value of the shear resistance of the grease (τ_m) was determined by the formula:

$$\tau_m = \frac{P}{F_m}, \quad (1)$$

where P – the compressive load applied to the punch of the device, at which the lubricant displacement begins, N; F_m – the surface area of the hole in the matrix, m^2.

The quality of sealing greases for threaded connections was evaluated by the efficiency factor (k_{ef}). To assess it, the casing was screwed together with the application of different types of lubricants to the threaded connections, aged for 15 hours, and then pressurised with the creation of internal overpressure to check the tightness of the connections. It was determined by the formula:

$$k_{ef} = \frac{P_n}{P} \times \frac{i_n}{i}, \quad (2)$$

where P – the critical pressure at which the tightness of a threaded connection screwed without lubrication occurs, MPa; i_s – the dry friction coefficient; P_n – the critical pressure at which tightness of a threaded connection screwed with lubrication occurs, or the maximum allowable pressure for the casing if the tightness of the connection is not failed, MPa; i – is the friction coefficient in the presence of lubrication.

Results and Discussion

Complications and accidents during the construction and operation of oil and gas wells, such as pipe separation at coupling joints or falling pipe sections, are often the result of difficult mining and geological conditions in the casing. This can lead to intercasing pressures and interstitial flows, as well as complications during casing cementing and well operations. Various complications arise as a result of threaded casing connections being depressurised, the most difficult of which is intercasing pressure (ICP). Failure of standard threaded connections is responsible for 70% of all casing-related complications (Kotskulych, 2007). The negative consequence of such complications is a decrease in well production rate, material losses, and damage to subsoil and the environment. Due to the high permeability of gas, the loss of well casing tightness in the process of gas field development is the most dangerous. An analysis of industrial materials and literature on the issue of leakage of pipe threaded connections allowed developing a qualification of the causes of these violations (Table 1).

Table 1. Classification of causes of threaded joints leakage

Incorrect strength calculation of the columns	Violation of casing assembly technology	Wear of casing strings
1. Incorrect consideration of internal overpressure during various operations in the casing. 2. Failure to take into account the increase in axial loads when the temperature changes, excessive external and internal pressures. 3. Failure to take into account the simultaneous action of internal pressure and tensile load.	1. Running pipes with defective threaded connections. 2. Mismatch of thread type and lubricant to well conditions. 3. Creating an internal pressure that exceeds the permissible one. 4. Poor connection of column sections. 5. Lack of control over torque values when screwing threaded connections. 6. Incorrect seating of the pipe in the coupling when screwing them together. 7. Uncontrolled screwing speed. 8. Mismatch of temperature conditions. 9. Damage to the thread. 10. Incorrect scheme of applying forces to the pipe.	1. Wear and tear of drill pipes and locks. 2. Wear and tear of bits and catching tools. 3. Corrosion. 4. Hydroabrasive wear.

Source: developed by the authors

The reasons for the loss of casing integrity at the Shebelynka SDD fields are presented in Table 2. The elimination of these complications and accidents requires significant funds, reduces the payback period, and causes large losses for the companies. Sometimes wells have to be abandoned due to casing accidents. The main causes of casing accidents are: incorrectly selected well design for the geological conditions of their construction; casing leaks due to damaged threaded connections. The required tightness of threaded connections can be achieved in the following ways: using different sealing materials; creating threaded connections with tightness units, or a simultaneous combination of both methods (Chernova & Kuntsiak, 2016). Coupling joints with leakage units, such as TTC, are considered promising. However, deviations in the manufacture of such connections, which are allowed by DSTU 8932:2019 (2019), significantly reduce their reliability. The sealing of threaded connections is achieved by tightly fitting the threads on the sides of the profile after screwing the connections, but the screw channel between the tops and bottoms of the threads must be filled with sealant (Rymchuk *et al.*, 2019). In the case of high-performance sealants, the tightness of the pipe coupling joint can be increased to a pressure that corresponds to the strength of the pipe body. Thus, the tightness of casing threaded connections depends primarily on the size and shape of the screw channel and the properties of the sealant filling this channel.

Table 2. Leakage of casing strings at Shebelynka SDD fields

Area, field	No. of a well	Production casing diameter, m	Well purpose	Causes of leakage
Yulivske	25	0.146	exploratory	Screwing of threaded connections with low torque values
Muratovske	51	0.146 × 0.168	operational	Use of low-performance lubricants. Screwing of threaded connections with low torque values
Zakhidno-Shebelinske	7	0.140 × 0.168	operational	Use of low-efficiency lubricants
Lychkivske	52	0.140 × 0.168	operational	Use of low-performance lubricants. Screwing threaded connections without torque control
Lychkivske	54	0.146 × 0.168	operational	Use of low-performance lubricants. Screwing threaded connections without torque control

Source: developed by the authors on the basis of industrial material

In addition, the following factors can be identified that affect the tightness of a tapered casing threaded connection accuracy of threading in the coupling and on the pipe; length of the working part of the thread; deviation of the angle of inclination of the threaded part, pitch, height of the thread profile; taper and ovality of pipes and couplings; value of axial tension of the thread when screwing; duration and nature of the load and pressure; viscosity of the pressure generating agent (liquid or gas) and the degree of its destructive effect on the sealant and thread metal. It was established that the efficiency of using the strength of casing material depends on the strength and tightness of threaded connections, which are determined by: the type of connection profile and precision of manufacturing of thread elements; type of sealant and its properties; value of screwing torque; value of axial tensile load; value of internal and external overpressure.

The results of research on the contact surface of the pipe and coupling of leaky threaded connections by V.Ya. Vasylyshyn *et al.* (2020) showed that when the permissible value of the screwing torque is exceeded, expansion (shearing, crushing) of one, two or more thread turns occurs on both the coupling and the pipe. Therefore, it can be concluded that such surface disturbances can cause not only liquid or gas leakage, but also a significant decrease in the tensile strength of threaded connections. To increase the tightness of the contact between the elements of threaded connections, various lubricants were used, including anaerobic sealants, the consistency of which should be sufficient to prevent their displacement from the gaps of the threaded connection (Femiak & Zelinskyi, 2024a; 2024b).

Researchers such as V. Vasylyshyn (2017) and Y. Mou *et al.* (2024) believe that the main cause of leakage of threaded connections is their under-seating due to incomplete selection of axial tension and insufficient screwing torque. The amount of torque depends to a greater extent on the size of the gaps in the thread, taper deviation, profile height, number of turns with an incomplete profile, etc. In addition, the grease that fills the gaps under pressure takes on part of the tensile load, reducing contact pressures on the contacting surface areas. Therefore, the main criteria for the correctness of screwing joints are the amount of tension and screwing torque, which requires the development of reliable control tools and technologies for their use. According to DSTU 8932:2019 (2019), the criterion for the tightness of threaded casing connections is to control the value of the conditional axial tension, the value of which is regulated by this standard when screwing elements both manually and using mechanical devices.

Pipes with a triangular thread profile: when hand screwing galvanised or phosphated couplings to pipes, the tension must be equal to A (distance from the end of the coupling to the end of the thread on the pipe when screwed together by hand). Maximum deviations are ±3.2 mm. After screwing the pipe and the coupling on the machine, the end of the coupling must coincide with the end of the thread on the pipe. Maximum deviations are ±3.2 mm. Casing pipes with trapezoidal coupling threads (OTTM): when manually screwing the couplings with pipes, the tension should be (14 ± 3) mm. After screwing the pipe and the coupling on the machine, the end of the coupling should coincide with the end of the thread on the pipe or not reach it by no more than 5 mm. OTTG pipes: when screwing the couplings to the pipes by hand, the tension must be (10 ± 2) mm. After screwing the pipe and the coupling on the machine, the pipe end face and the coupling stop should be in contact along the entire perimeter of the joint of the stop surfaces. A gap of <1 mm between the pipe and coupling bearing surfaces is permissible (for B pipes).

However, this criterion cannot be considered reliable, mainly due to deviations in the geometric parameters of the threads, uneven surface conditions, and different screwing conditions. Therefore, the main criterion for screwing should be the torque value, which is regulated depending on the strength group of the pipe material, wall thickness and pipe diameter. To ensure the tightness of threaded connections of casing pipes, the following requirements must be met during their manufacture the maximum total gap between the mating threads of the pipe and the coupling should not exceed 0.3 mm; the non-straightness of the cone formation should not exceed 0.04 mm; the coupling should be screwed onto the pipe in compliance with the torque values recommended by; threads on high-strength pipes should be cut on special machines; and high-performance sealants should be used.

To seal threaded connections, methods for applying a thin layer of sealing material to the thread surface were developed by Ukrainian scientists. The most reliable way was to apply a layer of soft metal (aluminium, zinc) inside the coupling by electrometallurgy (Kotskulych & Tyshchenko, 2009). This method also has significant disadvantages, such as the need for additional expensive equipment, energy and time consumption, and such metals often do not withstand corrosion from aggressive environments found in the subsoil.

According to ISO 13679:2019 (2019) and ISO 11960:2020 (2020), the main criterion for the quality of threaded casing connections is torque, which depends on the strength group of the steel, the diameter of the pipe and its wall thickness. The method of resealing the joints is widely used. The method is based on the use of a highly elastic compound. However, this method is ineffective due to significant drawbacks, namely: the need to create high internal pressure in the process of pressing the compound into the threaded connection, which can damage the pipe body; low adhesion of the highly elastic compound to the metal surface covered with a hydrocarbon film.

A method of sealing threaded connections using fluoroplastic sealing material (FUM tape) was also developed. The method is quite simple and relatively reliable; the fluoroplastic tape is non-toxic, plastic and has sufficiently high sealing properties. The disadvantage of this method is that when screwing threaded connections using FUM tape, there may be cases of loosening of the connection or even spontaneous loosening in the well, which can lead to leakage of the connections. This is due to the low adhesion force of the fluoroplastic sealing material to the thread surface. Amoco (USA) successfully used cathodic protection, which reduces fluid flow through casing by 75% (Barrett & Taylor, 1976).

Patent No. 73192 (2005) proposes a method of cycling casing over the wellhead during casing run. In this case, the threaded connections are screwed with a regulated torque value, which is monitored using a torque meter, then, without removing the casing from the wedges, the threaded connection is loaded with an axial load equal to the weight of the casing. After that, the casing is unloaded onto the wedges again and screwed down with a regulated torque value. The load-tighten cycle is repeated until the connection no longer tightens after the next load. This method is very time-consuming, which may be unacceptable when fastening deep wells.

In industrial conditions, a method of tightening threaded connections of casing strings run into the well was tested, the essence of which is that a torque is applied to the casing string run into the well with a simultaneous increase in excessive external pressure. Increasing the pressure makes it possible to use torque transmission more efficiently, increase the tightness of threaded connections and thereby restore the casing string's tightness. However, this method is too complicated to implement and cannot be used after cementing the casing. O-rings made of elastic materials, such as fluoroplastic, were also used to seal the threaded connections of casing pipes. Hydraulic tests of threaded connections with fluoroplastic O-rings showed their high reliability, but there are cases when these rings were destroyed by friction during screwing.

The Hydril company (USA) developed recommendations for screwing and running casing into the well (TenarisHydril running manual, n.d.), which lists the following requirements to ensure tightness: the nipple should be inserted into the coupling sequentially and carefully so as not to damage the thread or screw it through the thread; the start of screwing should be slow until the first thread turns are engaged; if screwing is done without force, the speed can be increased; when mechanical wrenches are used, they should grip the pipe as close to the thread as possible to avoid distortion during screwing; when screwing, do not exceed the recommended torque values; during screwing, the pipe and the coupling should be heated gradually and evenly.

An important task was to choose the right sealing greases or special sealants that must meet certain requirements, in particular, withstand high pressures and temperatures, and aggressive environments (Xie, 2021; Xie *et al.*, 2021). This is a fairly simple and reliable way to achieve the required tightness of casing threaded connections, which consists in filling the structural and technologically necessary gaps with sealing materials (sealants), which also serve as a lubricant to facilitate the screwing process. The following requirements are imposed on such materials: the required consistency, sufficient to prevent the pressure of liquids or gas from removing it from the thread gaps; consistency of properties over time and with temperature changes within a certain range; good lubricating properties; prevention of jamming when screwing threaded connections. The most important criterion is the required consistency of the material.

There are a number of such materials (mainly grease-based greases) that were used for screwing threaded connections of oil pipes. The most common graphite grease is USSA, which consists of 65% solidol and 35% silver graphite. P-2 MWP grease is based on 18.4% machine oil with 4.6% aluminium stearate, 14% silicone fluid No. 5, 18% graphite, 28% zinc and 17% copper. Graphite in these greases acts as an anti-friction material. Graphite properties are unchanged at high temperatures (200-2,000°C). The disadvantage of graphite greases is that the permissible specific pressure for it should not exceed 3-4 MPa. Higher pressures cause the destruction of the graphite film, which causes seizure when screwing threaded connections. These lubricants are used in wells with an internal pressure in the casing string of no more than 13 MPa.

Studies conducted at the Ukrainian Research Institute of Natural Gases showed that polymer alloys based on epoxy resins, in particular, the US-1 sealing grease, have the necessary sealing qualities, strength, elasticity and resistance to loads, as well as chemical stability to hydrocarbons. Its composition includes the following components: K-153 compound, which is ED-5 resin plasticised with MGF-9 polyester and thionol; hardener – cubic hexamethylene diamine residue; fillers used to enhance sealing properties and reduce friction forces that occur when fastening joints. US-1 has a high sealing capacity (up to 50 MPa). Disadvantages of US-1 are: toxicity, which worsens sanitary and hygienic working conditions and pollutes the environment; rapid precipitation of metal fillers (powders and powders); increase in pipe screwing torque (by 40-60%); rapid curing (application time of about 1.5 hours); difficulty of use at temperatures above +10°C (the need to heat the lubricant and the threaded end of the pipe), inseparability of the joint (after the lubricant hardened, the joint must be heated to a temperature of 300°C to unscrew it).

Synthetic lubricants were also used to ensure the tightness of threaded connections. The developed synthetic threaded joint lubricant was designed to improve the tightness and corrosion and fatigue resistance of threaded joints of oilfield tubular goods and downhole motors. Synthetic sealing grease (SG-1) was made on the basis of alkyl alkylresorcinol epoxyphenolic resin with fillers. This grease has high adhesion, helps to effectively protect threads from corrosive substances, and increases wear resistance during repeated screwing and loosening. The disadvantages of this grease are: it cannot be used at temperatures below -40°C and above +100°C; when used, it is necessary to carefully prepare the threaded connections; very high viscosity (before applying to threaded connections, it requires dilution with oil). Table 3 provides recommendations for the use of sealing materials for casing in different types of wells.

Table 3. Types of sealing materials for casing in different types of wells

Well type	Thread	Lubricant	Temperature application, °C	Permissible internal pressure, MPa
Oil	Triangular	P-2 MVP	-5 ± 100	12.7
	Triangular	US-1	0 ± 120	22.4
	Triangular	P-402	-50 ± 200	16.2
	Triangular	FUM tape	-20 ± 200	18.9
Gas, gas condensate	TTC, CC	P-2 MVP	-5 ± 100	23.1
	Any	US-1	0 ± 120	25.7
	TTC, CC	P-402	-50 ± 200	17.5
	Any	FUM tape	-20 ± 200	24.6

Source: developed by the authors based on Y. Kotskulych & O. Tyshchenko (2009)

Bestolife produces a sealing grease for threaded connections consisting of synthetic and amorphous graphite and non-metallic additives (Bestolife® metal free, n.d.). The temperature resistance of the grease is over 200°C. Shell silicone thread lubricants are used to seal threaded connections. These lubricants are a mixture of metal and graphite powders evenly distributed in a silicone base with a mass fraction of 36%. The solid components of the grease, which have a mass composition of 25%, are a mixture of graphite and lead powders and zinc dust. The basis of the modified thread grease is a lubricant mixture that, in combination with powdered metals and graphite, increases the tightness of threaded connections under various operating conditions. The above-mentioned greases are manufactured outside Ukraine and require significant funds, so an alternative analogue of the sealing grease was developed. The characteristics of the components of the developed grease are given below. Carbamide resin of the KF-MT-D or KF-MT-F grades is a homogeneous suspension of white to light yellow colour, free of impurities, non-flammable and non-explosive. The physical and chemical properties of carbamide resins are shown in Table 4.

Table 4. Physical and chemical properties of carbamide resins

Name of property (constant) and unit of measurement	Physical value with maximum deviations	
	KF-MT-D	KF-MT-F
1. Appearance	Homogeneous suspension from white to light yellow colour without foreign inclusions	
2. Mass fraction of dry residue, %	61 ± 1	66 ± 2
3. Mass fraction of free formaldehyde in 24 hours after manufacture, % not more than	0.15	0.15
4. Conditional viscosity (at 20 ± 0.5°C) according to the viscometer VZ-246, with a nozzle diameter 4 mm, s	50-90	80-100
5. Concentration of hydrogen ions, pH	7.5-8.5	7.5-8.5
6. Gelatinisation time: at 100°C, s	50-70	50-70
7. Maximum miscibility of the resin with water (at 20 ± 1°C) in the ratio by volume, not less than	1:1-1:2	1:2-1:4
8. Density, kg/m^3	1,260 ± 0.005	1,270 ± 0.005

Source: developed by the authors on the basis of TU U 24.1-32358806-005:2009 (2009)

The organophilic aerosil changes the volumetric and mechanical properties of the grease, significantly increasing its hydrophobicity and the strength of molecular interaction between the grease and the metal surface of the thread. The grease contains organophilic aerosil of AM-200, AM-300 or AM-380 grades, which have the properties shown in Table 5.

Table 5. Physical and chemical properties of organophilic aerosil

Indicators	Aerosil brand		
	AM-200	AM-300	AM-380
1. Appearance		White loose powder	
2. Specific surface, m^2/kg	200 ± 25	300 ± 30	380 ± 30
3. pH of aqueous suspension, not less than	3.6-4.3	3.6-4.3	3.6-4.3
4. Bulk density, g/l, uncompressed/pressed	60/120	60/120	60/120
5. Moisture content, % (dried at 105°C)	-	1.5	1.5
6. Hydrophobicity, %, not less than	90.0	98.0	99.0
7. Avergae particle size, μm	12	7	7
8. Mass fraction of SiO_2 in terms of hardened substance, %, not less than	99.9	99.9	99.9
Porosity		Porous	

Source: compiled by the authors based on I. Pertsev (2010)

Graphite was added to give the lubricant extreme pressure properties. White spirit, acetone, petrol or diesel fuel was used as a humectant for the aerosil. The humidifier ensures the uniform introduction of hydrophobic organophilic aerosol into the liquid carbamide resin and increases the frost resistance of the grease. Ammonium chloride ensures polymerisation of the grease in a screwed threaded connection within 6-12 hours. All components of the grease were produced in Ukraine and are safe in terms of harmful effects on personnel and the environment.

The above properties of the developed grease and some well-known and practically used greases were determined in the course of the study. The most important parameter was the adhesion force, which characterised the ability of the grease to adhere to the thread surface and increase this value over time. Based on the results of the study of the adhesion force, a graph was constructed (Fig. 2), which shows that immediately after applying the lubricant to the surface of the metal disc, the adhesion force is low.

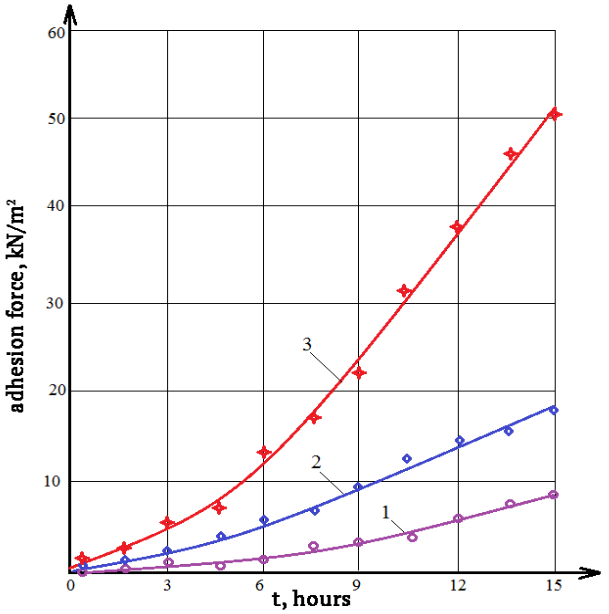

Figure 2. Changes in the adhesive properties of sealing greases over time

Note: 1 – USSA grease; 2 – R-2 MVP grease; 3 – US-OT grease

Source: developed by the authors

This is important for the process of casing screwing, since the adhesion force affects the torque value, which should be applied only to select the radial tension of the threaded connection. The maximum time for testing the adhesion force was chosen to be commensurate with the average time of casing run into the well, since at the end of this process, i.e. before cementing, the casing must be sealed to ensure the formation of a high-quality fastening. Over time, the adhesion strength of all the tested lubricants increases, but with varying intensity. After six hours from the start of applying the greases to the metal disc, the developed grease begins to intensively increase the adhesion force due to the polymerisation reaction and reaches its maximum value (more than 50 kN/m^2) after 15 hours of curing, which is 2.9 times higher than the P-2MVP grease and 5.7 times higher than the USSA grease. The ability of the lubricant to resist its displacement from the technological gaps of the threaded connection also depends on the value of the adhesion force, which is confirmed by the results of the studies presented in C. Teodoriu *et al*. (2020). These studies concern the tightness of Oil Country Tubular Goods (OCTG) threaded connections using five different types of compounds and a programmable digital rheometer under the influence of shear rate, temperature, and various loading conditions. The experimental results showed that the low viscosity properties of the compounds did not ensure the tightness of the threaded connections and also had low heat resistance (some samples lost their sealing ability at 70°C). Carbamide resin, which is the basis of the grease developed by the authors, has a higher temperature resistance (150-170°C) and the gelatinisation time at 100°C is 50-70 s, meaning that the grease quickly gains consistency and is retained on the thread surface.

Another important parameter that determines the amount of torque for screwing casing threaded connections is the friction coefficient. Its value is influenced by the ability of the lubricant to fill in the irregularities of rough thread surfaces, minimise the friction force during screwing of threaded elements and provide anti-seize protection. The results of the tests are presented in Table 6, from which it can be concluded that the coefficient of friction of a steel-steel pair using US-OT grease is on average 64% lower than that of other greases.

Table 6. Results of the grease study

Grease name	Lubricant adhesion, kN/m^2	Shear resistance of the grease, MPa	Lubricant friction coefficient	Lubricant efficiency factor
USSA	4.75	0.124	0.088	1.41
R-2 MVP	2.47	0.135	0.069	2.01
US-OT	7.02	0.145	0.046	3.4

Source: developed by the authors

The relevance of this parameter is confirmed by the results of studies of the physicochemical and tribological properties of anti-seize thread lubricant presented in W. Zhimin *et al*. (2021). The composition of the extreme pressure grease includes base oil, di-aromatics and graphite powder mixed with a viscosity index improver, antioxidant and rheological additive. Thermal stability, anti-wear and antifriction properties were studied, but there is no information on its sealing ability. In the absence of lubrication, the phenomenon of local welding and diffusion may also occur on the screwed surfaces due to high contact pressures, as noted in the work of K.K. Kakulite & B. Kandasubramanian (2019). To avoid this negative phenomenon, it was proposed to use solid lubricants, hard ceramic coatings such as titanium nitride, and synergistic coatings of copper or silver based on PTFE. However, in the opinion of the authors of the current study, such solutions are difficult to implement and use in comparison with the application of grease lubricants to the threaded connection.

The required service life of the casing threaded connection also depends on the corrosion processes occurring on the metal surface under the influence of aggressive media occurring in the subsoil (e.g. hydrogen sulfide, carbon dioxide, acidic water, magnesium salts). Therefore, its protection from contact with aggressive environments is also important and should be counteracted by any anti-corrosion coating, including lubricants. In the work of D. Ernens *et al*. (2019) confirmed the need for phosphate-conversion coating of the surface of casing threaded connections and the application of grease lubricants to prevent corrosion processes and reduce friction forces during screwing. The developed US-OT grease has the necessary hydrophobic properties to protect the threaded connection from formation water, but additional research is needed to assess its resistance to other types of aggressive media.

In the process of running and cementing casing strings, the dispersed medium of the flushing fluid or cement mortar under pressure can cause the lubricant to be displaced from the technological gaps of the threaded connection. The ability of the lubricant to counteract this negative phenomenon is characterised by the shear resistance of the lubricant, in other words, its ability or the contact between it and the surfaces of the screwed elements to resist the mutual displacement (sliding) of the layers under the action of tangential (shear) stresses arising from any external force. The results of the study of the shear resistance of various greases are presented in Table 6, which shows that the highest value of this parameter is characteristic of the proposed grease, and accordingly, it has the highest resistance to extrusion from the technological gaps of the threaded connection during the curing process. The developed grease is recommended to improve the tightness of all types of casing threaded connections regardless of their design, since technological gaps are a potential channel for fluid penetration during well operation. The study by H. Xu *et al*. (2023) investigated the permeability of premium casing threaded connections with metal-to-metal sealing elements and confirmed the need to use sealing lubricants despite the presence of a sealing assembly.

The efficiency of screwing casing threaded connections depends on the composition of the lubricant, especially the presence of solid particles (e.g., particles of any metal), which increase the coefficient of friction and can damage the rubbing surfaces during screwing, as noted in K. Inose *et al*. (2016). This statement is consistent with the authors' research, since the developed formulation does not contain any solid particles, which has a positive effect on the screwing process. In general, the quality of sealing greases for threaded connections was assessed using a complex parameter called the efficiency factor. It describes the ability of the lubricant to provide low values of the friction coefficient when screwing a threaded connection and its tightness under internal pressure. An example of calculating the effectiveness of US-OT lubricant for a casing pipe of the OTTM type -146 × 7.7 D. The value of the internal pressure at which the stresses in the pipe body reach the yield strength of 35 MPa. The leakage of the threaded connection without the use of lubricants was observed at a pressure of 26.3 MPa. When USSA grease was applied to the threaded connection, the leakage occurred at a pressure of 28.04 MPa. Then the efficiency factor is equal to:

$$k_{ef} = \frac{28.04}{26.3} \times \frac{0.117}{0.088} = 1.41. \quad (3)$$

When applying P-2 MVP grease to a threaded connection, a leakage occurred at a pressure of 31.2 MPa, and the efficiency factor is equal to:

$$k_{ef} = \frac{31.2}{26.3} \times \frac{0.117}{0.069} = 2.01. \quad (4)$$

With the use of US-OT grease, no leakage was observed, so P_n = 35 MPa, and the efficiency factor is equal to:

$$k_{ef} = \frac{35}{26.3} \times \frac{0.117}{0.046} = 3.4. \quad (5)$$

The results of the study of the properties of different lubricants are presented in Table 6. The data obtained are also consistent with the conclusions presented by B. Yang *et al*. (2023) and F. Ye *et al.* (2023), who presented the results of testing the tightness of casing after sealing threaded connections with lubricants and noted that the consistency of the lubricant and the magnitude of the pressure gradient are crucial for maintaining tightness. The study of the sealing properties of lubricants for casing threaded connections is key to ensuring well reliability, as they not only reduce friction during screwing, but also play a critical role in sealing gaps and preventing the flow of formation fluids. The analysis of the current state of the art in the use of sealing lubricants shows that work on the development of sealing lubricants remains relevant.

Conclusions

The results of the experimental work showed that the formulation of the developed US-OT grease, which consists of Ukrainian components and does not contain harmful substances, is compliant with the formulation of the developed grease, as well as its high efficiency in ensuring the tightness of threaded connections of casing pipes intended for oil and gas wells. The article highlights the results of the analysis of the main properties of the developed grease, including adhesion strength, shear resistance and friction coefficient. The grease is recommended for use with all types of casing connections, regardless of their design features, the presence of auxiliary sealing units and the type of coating applied to the threads. This is based on the grease's ability to optimise the screwing process, fill technological gaps in the joint and, after the polymerisation reaction is complete, ensure its reliable sealing.

The qualitative characteristics of the grease were evaluated using the efficiency coefficient, the growth of which correlates with an increase in the degree of compliance of the grease with the stated requirements. Over time, there is an increase in the adhesive properties and shear resistance of the sealing grease; the cured material acquires hydrophobic characteristics, and the threaded connection of the casing demonstrates tightness at pressures that meet the maximum permissible values. The lubricant is compatible with the materials in contact, has no corrosive effect on casing and sealing elements and is safe for personnel.

Future research will be aimed at analysing the functionality of the lubricant in conditions that simulate the operation of deep wells, in particular in the presence of aggressive chemical environments (such as hydrogen sulfide, carbon dioxide, highly mineralised formation water, chemogenic deposits) and under the influence of high temperatures and pressures. Since there is a growing demand for the creation of environmentally friendly lubricants (metal-free, biodegradable), the use of nanoparticles in lubricants to improve their properties, modern methods such as scanning electron microscopy for analysing thread damage; thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) for assessing the thermal oxidative stability of lubricants should be used for further research.

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Conflict of Interest

None.

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Розробка та дослідження властивостей герметизуючого мастила для різьбових з'єднань обсадних труб

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Анотація. Герметичність різьбових з'єднань обсадних колон є критично важливою проблемою, оскільки вона безпосередньо впливає на надійність кріплення свердловин, а відтак на їхню безаварійну та тривалу експлуатацію. Зважаючи на те, що перед нафтогазовою галуззю поставлено завдання максимального забезпечення потреби енергоносіїв власним видобутком, зазначена проблема залишається актуальною. Метою роботи було дослідити властивості розробленого герметизуючого мастила для різьбових з'єднань обсадних труб та підтвердити його ефективність порівняно з іншими використовуваними засобами. Для проведення досліджень у роботі використано аналітичний та експериментальний методи. Проаналізовано промисловий матеріал з якості кріплення свердловин та встановлено, що в багатьох свердловинах наявні дефекти у їхньому кріпленні, котрі пов'язані з негерметичністю різьбових з'єднань обсадних труб. Проведена класифікація причин порушень працездатності різьбових з'єднань та виділено основні чинники, що впливають на їхню герметичність. Розроблено герметизуюче мастило, що складається з карбамідної смоли, органофільного аеросилу, графіту, зволожувача аеросилу та хлористого амонію. Для оцінювання ефективності розробленого мастила було визначено такі показники: коефіцієнт тертя на поверхні пари «сталь-сталь», сила адгезії, опір мастила на зсув, герметичність різьбового з'єднання у процесі його опресування внутрішнім тиском та коефіцієнт ефективності. Встановлено, що запропоноване мастило має вищу початкову силу адгезії, порівняно з іншими, і до того ж вона постійно зростає у процесі полімеризації та досягає максимальної величини через п'ятнадцять годин тверднення; мастило має менший коефіцієнт тертя, більший опір на зсув та значно вищий коефіцієнт ефективності. Проведеними дослідженнями підтверджено підвищення працездатності різьбових з'єднань обсадних труб із використанням розробленого мастила

Ключові слова: кріплення свердловин; коефіцієнт ефективності; надійність; ущільнююче мастило; сила адгезії

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Optimisation of the operation of a group of wells with different productive characteristics connected to a common collector

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Abstract. Optimisation of the operation of a group of wells connected to a single pipeline consists of the correct distribution of the pressure load between the wells, which ensures that there are no gas production losses at the group level, as well as the maximum involvement of each well in the production process. Therefore, the aim of the study was to establish the optimal technological mode of well operation, taking into account the connection of wells to a common collector with different working pressures at their mouths. This was achieved by redistributing the flow rate between wells, taking into account the gas reserves in the specific drainage volume, by installing a fitting at their mouths. The problem was solved by simultaneously solving two equations: an equation reflecting the constancy of the ratio between the well flow rate and gas reserves per unit of drainage volume, and an equation for the volumetric gas flow during adiabatic (i.e., without heat exchange with the environment) leakage through the fitting, which was described by the Saint-Venant-Wansel formula. Based on the solution of the problem and the performed calculations, it was established that three wells from the group were operated at reduced flow rates due to differences in residual specific drainage volumes, while the remaining wells exceeded the optimal gas flow rate parameters. Such a discrepancy was interpreted as evidence of inefficient utilisation of the resource potential of the field. A solution to the multi-objective problem was proposed, aimed at optimising the operating mode of a group of wells and the gas gathering network as a single integrated hydrocarbon production system. With this approach, a balance was achieved between the efficiency of hydrocarbon extraction and the uniformity of the load on the infrastructure. The outcomes of the study are expected to be useful in practice for establishing optimal technological modes of operation for wells with different production characteristics operating in a single collector

Keywords: pipeline; flow rate; fitting; pressure; gas; field; gathering system

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Introduction

Depending on the pipeline system configuration, hydrocarbon products gathering systems were classified as collector and non-collector schemes. In gas field development, it was common for products from several wells to be fed into a common pipeline (collector), through which they were transported to a gas processing plant (GPP). One of the key operational tasks in managing such a system was to maintain optimal operating conditions for wells connected to a common collector.

In their study, A.V. Uhrynovskyi *et al*. (2022) analysed approaches to organising product gathering systems at oil fields. It was concluded that creating a single universal system was impractical because of the unique geological and technical conditions characterising each field. In particular, several factors were identified that determined the specifics of the gathering system, the layout of wells, the physical and chemical properties of reservoir fluids, the level of remaining reserves, the climatic conditions of the region, the selected well operation methods, and the volume of hydrocarbon products. Thus, the necessity of an individual approach to the design of gathering systems for each specific field was emphasised.

According to O. Stanley *et al*. (2021), the operation of wells in heterogeneous reservoir conditions was accompanied by several technical problems. They emphasised that differences in reservoir properties caused significant differences in pressures of wells and flow rates, even when wells were located close to each other, which significantly complicated the effective operation of the gathering system. It was noted by the authors that considerable heterogeneity of reservoir rocks could lead to major differences in wellhead pressure and production rate even among wells situated within a short distance of each other. It was established that connecting such wells to a common pipeline led to a redistribution in the system: wells with high pressure could suppress low-pressure ones, limiting their productivity to a minimum level. It was also emphasised that well productivity was closely dependent on wellhead pressure; therefore, a change in the operating mode of one well could significantly affect the performance of other wells within the system. In the study by I.W. Purnomosidi *et al*. (2024), effective methods for regulating the operation of gas wells were explored. It was pointed out that one of the main ways to control well productivity was to control the pressure at the wellhead or the inlet of the tubing shoe. The most common practical method was the creation of backpressure at the wellhead using a fitting. The use of downhole fittings had not become widespread due to difficulties associated with their installation and maintenance. A key aspect of the study was the observation that adjusting the cross-sectional area of the choke opening allowed for precise regulation of the well flow rate according to reservoir conditions.

In the works of T.M. Nesterenko *et al*. (2021) and S. Bekov *et al*. (2024), the process of achieving a stable technological operating mode of wells after adjusting fitting parameters was analysed. It was noted that after adjusting the passage area of the fitting, the well had to operate in the set mode for a certain period until stabilisation was achieved. This stable mode was characterised by constant flow rate, bottomhole and annular pressures. It was emphasised that the technological operating mode was established taking into account a set of limiting factors and determined the operating conditions under which the maximum possible gas flow rate was achieved without damaging the integrity of the formation or technical equipment.

The study by L.V. Moroz *et al*. (2023) was devoted to analysing the formation of the technological mode of gas well operation at industrial enterprises. It was noted that such modes were developed quarterly by the geological service of the enterprise and approved by the chief geologist and chief engineer of the gas production department. Special attention was given to determining the optimal operating conditions, which required the identification of the leading factor or group of factors most influencing production efficiency. It was highlighted that the rational design of a technological regime requires taking into account a wide range of parameters: well construction, the stability of gas-bearing formations to destruction, geological structure (multi-layered, heterogeneous, sequence of formations), physical and chemical characteristics of gas (water and condensate content), features of the operating scheme (group placement of wells, connection to a header), as well as the presence of complications such as salt deposits.

In the studies by Q. Zhang *et al*. (2022), J. Wu *et al*. (2022), and M.S. Al-Kadem *et al*. (2024), designed solutions used to implement the specified operating mode of wells were reviewed. It was stated that the most common means of control are fittings of various designs – both straight and angular, as well as fittings such as throttle washers. The latter received special attention due to their simplicity, reliability, and efficiency. An orifice-type choke consisted of a metallic disc with a hole of a specified diameter, installed at the wellhead in place of the sealing ring between two flanged joints. In the works of B. Tan *et al*. (2024) and J. Wu *et al.* (2022) presented an innovative technical solution to improve the efficiency of well pressure control, a choke equipped with an electronically controlled control system with an electric drive. It was noted that the introduction of such a system made it possible to significantly improve the accuracy of pressure control and reduce the response time to changes in operating conditions. The electronic control made it possible to remotely adjust the throttle parameters in real time, providing continuous pressure monitoring and rapid system adjustment. This approach also significantly improved personnel safety, as it eliminated the need for manual intervention at the well site.

Although numerous studies were devoted to various approaches for organising production gathering systems in oil and gas fields, a clear methodology for selecting throttle washers for wells with different performance characteristics connected to a common collector was not found in the current scientific literature. This gap indicated the need for further research and development aimed at optimising well operation regulation under heterogeneous conditions, which was essential for enhancing production efficiency and operational reliability. The aim of this study was to determine the optimal well operation mode, taking into account their connection to a common collector at different wellhead pressures.

Materials and Methods

The material used in this study was data on the operation of gas wells operating with wellhead throttle washers and sharing a common gas gathering collector. Optimisation of a group of wells connected by a single pipeline was based on the correct balancing of the pressure load between them, which avoided a decrease in overall gas production and ensured efficient operation of each well. To meet these requirements, a constant ratio between the well flow rate and the gas reserves per unit volume of the drainage area had to be maintained, specifically:

$$\frac{q(1)}{\alpha\times\Omega_1}=\frac{q(2)}{\alpha\times\Omega_2}=\ \dots\ =\frac{q(i)}{\alpha\times\Omega_i}=\text{const}, \quad (1)$$

where $q(i)$ is the flow rate of the i-th well, m^3/d; $\alpha\times\Omega_i$ is the gas-saturated drainage volume of the i-th well, m^3. According to the Saint-Venant-Wanzel formula, the volumetric gas flow rate during adiabatic (without heat exchange with the environment) movement through an opening (fitting, throttle washer) could be found by the formula:

$$q_g=\mu\times\omega_o\times\sqrt{2\times R}\times\frac{P_1\times T_o}{P_o}\times$$
$$\times\sqrt{\frac{1}{T_1\times M_g}\times\frac{k}{k-1}\times\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{k}}-\left(\frac{P_2}{P_1}\right)^{\frac{k+1}{k}}\right]}+, \quad (2)$$

where q_g is the volumetric gas flow rate under normal conditions, m^3/s; P_o, T_o are the pressure and temperature under standard conditions, Pa and K; ω_0 is the leakage rate, m/s; P_1, T_1 are the pressure and temperature at the inlet of the fitting, Pa and K; P_2 is the pressure after the fitting, Pa; μ – is the flow coefficient for the lemniscate nozzle μ = 0.95 - 0.98 increases with the Reynolds number and slightly decreases with P_1/P_2; k is the adiabatic coefficient, which changes little with temperature and molecular weight of the gas, so for practical calculations it can be taken with sufficient accuracy as $k=1.25$; $R=8{,}314.3$ J/(kg·K) is the standard gas constant; M_g is the molar mass of a gas, kg/mol. The application of this formula is limited by the critical pressure ratio:

$$\left(\frac{P_2}{P_1}\right)_{kr}=\frac{2}{(k+1)^{k/(k-1)}}. \quad (3)$$

This is a condition where the flow velocity reaches the speed of sound and the gas flow rate is maximum, i.e. formula (2) is applicable under the condition $\left(\frac{P_2}{P_1}\right)>\left(\frac{P_2}{P_1}\right)_{kr}$. If $\left(\frac{P_2}{P_1}\right)\leq\left(\frac{P_2}{P_1}\right)_{kr}$ then in formula (2) $\left(\frac{P_2}{P_1}\right)$ must be replaced with $\left(\frac{P_2}{P_1}\right)_{kr}$, i.e. take $\left(\frac{P_2}{P_1}\right)=\left(\frac{P_2}{P_1}\right)_{kr}$, then the maximum gas flow rate is:

$$q_g=\mu\times\omega_o\times\sqrt{2\times R}\times\frac{P_1\times T_o}{P_o}\times$$
$$\times\sqrt{\frac{1}{T_1\times M_g}\times k\times\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}. \quad (4)$$

To determine the diameter of the throttle washer, formulas (2) and (4) should be written in the following form:

$$d=\sqrt{\frac{4\times q_g\times P_o}{\pi\times\mu\times P_1\times T_o\times\sqrt{2\times R}\times\sqrt{\frac{1}{T_1\times M_g}\times\frac{k}{k-1}\times\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{k}}-\left(\frac{P_2}{P_1}\right)^{\frac{k+1}{k}}\right]}}}; \quad (5)$$

$$d=\sqrt{\frac{4\times q_g\times P_o}{\pi\times\mu\times P_1\times T_o\times\sqrt{R}\times\sqrt{\frac{1}{T_1\times M_g}\times k\times\left[\frac{2}{k+1}\right]^{\frac{k+1}{k-1}}}}}. \quad (6)$$

The diameter of the throttle washer was determined using formula (6), which ensures critical gas flow at a given gas flow rate q_g. After solving equations (1), (5), and (6) collectively, the required diameter of the throttle washer for each well was determined. The amount of residual drained gas reserves from the total volume of reserves in the wells was found using formula (7):

$$\Delta=\frac{Q_{inres}}{\Sigma Q_{res}}\times 100\%. \quad (7)$$

The gas flow rate for production optimisation was determined as the product of the total gas flow rate by wells and the value of the remaining drained gas reserves of the total reserves volume for each well:

$$q_2=q_t\times\Delta. \quad (8)$$

Results and Discussion

A group of six wells connected to a single pipeline was examined. Figure 1 shows a graph of the gas flow rate of each well as a function of the change in working pressure at the wellhead. The total gas flow rate of these wells was limited by the consumer and amounts to 34.35 thousand m^3/d. Under these conditions, the pressure in the reservoir is 20 atm, and at the inlet to the gas processing plant (GPP), the gas flow was throttled to a pressure of 5 atm.

The graphical dependence of the gas flow rate of six wells on the working pressure at the wellhead is shown in Figure 1. The horizontal axis shows the working pressure (P_w) in the range from 4 to 24 atm, and the vertical axis shows the corresponding gas flow rate (1,000 m^3/day). Each line corresponds to a separate well (well 1-well 6) and is approximated by a second or fourth-degree polynomial, which allows for accurate reflection of the change in productivity depending on pressure. Analysis of the graph shows a nonlinear dependence of flow rate on pressure at the wellhead. The most productive well is No. 2, whose flow rate at low-pressure values exceeds 20 thousand m^3/day. Conversely, well No. 6 shows the lowest production level, less than 2 thousand m^3/day under the same conditions.

This difference was caused by geological and technical features of the corresponding drainage intervals. The dependencies were an important basis for further optimisation of the gas collection system, as they allowed assessing the impact of changes in wellhead pressure on the intensity of each well and the group as a whole. Table 1 shows the gas flow rates of the wells at a reservoir pressure of 20 atm, the initial drained gas reserves and the accumulated production for each well. Well No. 6 has the lowest gas flow rate – 1.52 thousand m^3/day, which is only 4.4% of the total flow rate of the six wells. To ensure an even load between wells, according to formula (1), a constant ratio between the well flow rate and the volume of gas per unit of drained space should be maintained.

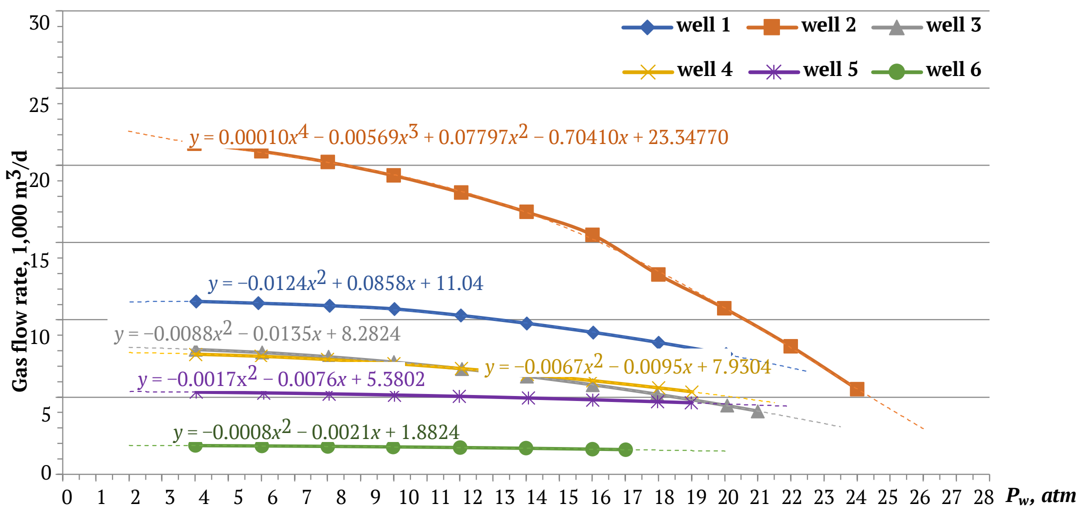

Figure 1. The influence of working pressure at the wellhead on gas flow rate

Source: created by the authors

Table 1. Operating parameters of wells operating in a common pipeline

Well	Gas flow rate (q_1), thousand m^3/d	Initial drained gas reserves (Q_{res}), million m^3	Accumulated gas production (Q_{pr}), million m^3	Pressure in the collector (P_{col}), atm
1	7.80	88.6	27.6	20
2	10.93	107.6	69.1	
3	4.49	82.5	46.9	
4	5.06	32.0	5.5	
5	4.55	32.5	7.3	
6	1.52	48.1	28.9	
Total	34.35	$\sum Q_{res} = 391.3$	$\sum Q_{pr} = 185.2$	

Source: made by the authors

Table 2 presents the results of calculating the well flow rate after optimising gas production, taking into account the amount of residual drained gas reserves from the total volume of reserves in the wells. Analytical results of gas flow distribution between six wells are presented to achieve optimal operating mode with limited total productivity. Optimisation involves ensuring the proportional distribution of production by the residual drained gas reserves of each well.

Table 2. Results of gas flow rate calculations for production optimisation

Well	Residual drained gas reserves (Q_{res}), million m^3	Residual drained gas reserves as a percentage of total reserves in wells Δ, %	Gas flow rate for production optimisation (q_2), thousand m^3/d	q_1 - q_2, thousand m^3/d
1	61.0	29.6	10.17	-2.37
2	38.5	20.7	7.11	3.82
3	35.6	19.3	6.63	-2.14
4	26.5	12.9	4.41	0.65
5	25.2	12.2	4.20	0.35
6	19.2	5.3	1.82	-0.30
Total	$\sum Q_{res} = 206.1$	100	34.35	

Source: made by the authors

Column 2 shows the value of residual drained gas reserves (Q_{res}, million m^3. The largest volumes of residual reserves are observed in well No. 1 (61.0 million m^3), and the smallest in well No. 6 (19.2 million m^3). Column 3 shows the share of each well in the total remaining reserves (%), which varies from 29.6% to 5.3%. Column 4 shows the optimal gas flow rate (q_2), thousand m^3/d, calculated according to the proportional model that takes into account the remaining reserves. According to the calculations, wells No. 2, No. 4, No. 5 demonstrate positive values of flow rate increase

($q_2 > q_1$), while wells No. 1, No. 3, No. 6 shows the need to reduce production ($q_2 < q_1$), which is recorded in column 5 as the difference between the current and optimised flow rates ($q_1 - q_2$). The calculated data indicate that it is possible to increase the efficiency of the entire group of wells by redistributing well flow rates, which avoids hydraulic squeezing of low-flow wells and ensures uniform hydrocarbon production.

Table 2 shows that there was a redistribution of well gas flow rates, taking into account the residual drained gas reserves. The results of the calculations show that wells No. 1, No. 3 and No. 6 should have higher operating gas flow rates by 2.37 thousand m^3/d, 2.14 thousand m^3/d and 0.30 thousand m^3/d, respectively. At the same time, the operating flow rates of wells No. 2, No. 4 and No. 5 should decrease by 3.82 thousand m^3/d, 0.65 thousand m^3/d and 0.35 thousand m^3/d, respectively. To distribute the gas flow rate between the wells according to Table 2, it was necessary to install choke washers with the appropriate bore diameter at the wellheads, which reduced the pressure in the collector. Table 3 shows the results of calculations of the operating parameters of six wells combined into one group to achieve the optimal production mode.

Table 3. Gas flow rate for production optimisation and required choke plate diameters

Well	Gas flow rate for production optimisation (q_2), thousand m^3/d	Working pressure at the wellhead for production optimisation, atm	Choke plate diameter, mm	Collector pressure for production optimisation, atm
1	10.17	12.52	6.043	5
2	7.11	23.03	3.726	
3	6.63	12.95	4.798	
4	4.41	22.23	2.986	
5	4.20	24.25	2.790	
6	1.82	7.50	3.989	
Total	34.35	-	-	-

Source: made by the authors

The main controlled parameters are: the target gas flow rate of each well (q_2), the operating pressure at the wellhead, the optimal diameter of the choke washer, and the pressure in the reservoir, which is the same for the entire group and amounts to 5 atm. The value of the gas flow rate for optimisation (q_2) ranges from 1.82 to 10.17 thousand m^3/d. The highest flow rate is provided for well No. 1, which requires the largest choke washer diameter – 6.043 mm at a wellhead pressure of 12.52 atm. At the same time, the lowest flow rate corresponds to well No. 6 (1.82 thousand m^3/d), which requires a choke washer with a diameter of 3.989 mm at the lowest wellhead pressure of 7.5 atm. The operating wellhead pressure varies depending on the well characteristics and is adjusted to ensure the required reservoir pressure at the agreed production rate. For example, for well No. 2 with a production rate of 7.11 thousand m^3/d, the corresponding wellhead pressure is 23.03 atm, which requires the installation of a washer with a diameter of 3.726 mm. The working pressure at the wellhead for optimising production in the presence of a choke washer can be found from Figure 1 with a known gas flow rate q_2.

The most common variant of the technological process of gathering products from wells is a collector scheme, in which the flow from several wells is combined into one pipeline and transported to the GPP. Pressure regulators or wellhead chokes were often installed to maintain the required pressure at the bottom hole or wellhead and ensure a given oil and gas production rate. In the study of H.S. Barjouei *et al*. (2021), the peculiarities of well operation in the presence of a two-phase filtration flow were analysed. The impact of phase (gas-liquid) interaction on the hydrodynamic parameters of operation, and changes in flow rate, pressure, and production recovery efficiency under such conditions, were examined. The obtained results allowed for a better understanding of the specifics of well behaviour in a two-phase filtration mode and could be used to improve models for forecasting and optimising well operations. The calculations were performed under the conditions specific to the Sorush oil field, taking into account the flow of a gas-liquid mixture. When evaluating these studies in the context of parameters influencing well performance, such as wellbore diameter, wellhead pressure, fluid specific gravity, and the gas-liquid phase distribution ratio, it should be noted that the effect of gas pressure behind the wellbore was not considered. Furthermore, it was observed that the main flow mode of the gas-liquid mixture through the fitting was critical.

In the works of MS. Dabiri *et al*. (2024) and T. Visawameteekul *et al*. (2024), the necessity of installing a wellhead fitting to control the technological mode of well operation and prevent such complications as the formation of a bottomhole cone and destruction of the bottomhole zone of the formation was described. The importance of the wellhead choke in regulating flow rate and optimising production for the entire collection network was also noted. The model was developed using multivariate regression and an optimisation algorithm. Data for the study were collected from 21 wells in seven fields in the Niger Delta region. The developed model investigated gas flow through the wellhead and the effect of the diameter of the wellhead and gas density on well productivity. Although the developed model involved a significant amount of data from 21 wells and provided accurate verification of values, it did not take into account the mutual influence of wells connected to a common pipeline.

In the study by Q. Zhang *et al*. (2022), the technical characteristics of the wellhead fitting were shown to play a critical role in optimising well production parameters. A hydrodynamic model was constructed based on the actual layout of the prefabricated reservoir to simulate the flow process. The distribution of the flow field and the pressure drop under various operating conditions were recorded. The findings demonstrated that pressure losses in the collector occurred both as a result of changing inlet conditions and due to variations in flow structure. It was noted that the study focused on comparing different types of throttling devices. The authors concluded that, under identical opening conditions, the pressure drop associated with a wedge-type throttle was lower than that observed with a flat-type throttle.

In the research conducted by S.K. Joshua *et al*. (2020), the optimisation of well operations was examined through variations in choke size, adjustment stages, and replacement frequency. The results indicated that a greater pressure differential at the wellhead fitting during the initial production phase resulted in a higher initial gas production rate. It was found that smaller wellhead fittings were more favourable than larger ones in terms of gas transport efficiency, with a choke diameter of 3 mm identified, through numerical modelling, as optimal. The issues related to the calculation of choke washers and pressure regulation were explored in the works of M. Bennis *et al*. (2020) and Q. Zhang *et al*. (2022). Although these studies focused on the analysis of pressure drops across throttling devices using computational methods, primary attention was given to the degree of choke opening and the hydrodynamic behaviour of the flow field.

In the work of I. Baselt & A. Malcherek (2022), a modernised form of the Saint-Venant-Wansel theoretical relationship for determining the gas flow rate from a system's flow element was presented. The studies conducted by Y.A. Rilwan & G.C. Nmegbu (2022), as well as by A.H. Al Salmi *et al*. (2023), addressed the role of flow control elements, particularly fittings and throttle washers, in gas well operations. It was established that the primary limiting components governing gas flow through wellhead equipment were the fitting and throttle washer. The choke was identified as a critical element designed to regulate the velocity of gas or liquid flow within limits acceptable for preserving the integrity of the productive formation. This regulation helped prevent the development of water or condensate cones, thereby reducing the risk of premature water breakthrough in the well. Furthermore, wellhead chokes were recognised as key tools in reservoir management, as they allowed for the control of individual well flow rates and the generation of the required pressure within the gathering collector, thereby enabling more efficient and balanced field operation.

The study of gas flow control was recognised as one of the critical tasks in the selection and installation of throttling devices in gas pipeline systems. In this context, X. Gu *et al*. (2024), and S. Kongkiatpaiboon & S. Apisaksirikul (2025) improved the design of valve sleeves to enhance the regulation of axial gas flow. Following these design improvements, eight numerical simulations were carried out at varying orifice sizes to analyse changes in the velocity field, pressure distribution, and aerodynamic noise within the flow channel for both design configurations. A comparative analysis of the two valve designs was also presented, focusing on their respective flow field structures and noise characteristics. The modelling results demonstrated that a properly increased orifice diameter in the throttling device could significantly improve the performance of the axial gas flow control valve, with noise levels reduced to below 100 dB at medium and small orifices.

Optimisation of the operation of a group of wells connected to a common collector was addressed through the rational distribution of pressure loads, with the aim of minimising production losses at the system level and maximising the individual potential of each well. The study was undertaken to determine the optimal technological modes for well operation, taking into account varying wellhead pressure values in a shared pipeline configuration. To address this objective, an approach was employed based on the simultaneous solution of two equations: the first describing the constancy of the ratio between well production rate and gas reserves per unit volume of the drainage area; the second characterising gas flow through the fitting under adiabatic conditions, following the Saint-Venant-Wansel formula. The results indicated that three wells within the group were operated at suboptimal flow rates due to limited residual drainage volumes, while others exceeded optimal output levels, highlighting a systemic imbalance in the distribution of load across the well network.

Conclusions

Based on the study, a method for solving a multi-objective problem aimed at the comprehensive optimisation of both the technological regime of individual wells and the operation of the gas gathering system as a whole was proposed. The application of this approach allowed not only for efficient hydrocarbon extraction but also for the balancing of the load on infrastructure elements, which is especially important for maintaining long-term field productivity. In this paper, a solution was presented for the operation of a group of wells with differing performance characteristics connected to a common gas pipeline. To evenly distribute the load among the wells, a system of equations was considered, one of which described the constancy of the ratio between the well production rate and gas reserves in the specific drainage volume, while the other, the Saint-Venant-Wantzel equation, characterised the gas flow through the flow element.

By establishing the correct technological mode of well operation, wellhead pressures were adjusted according to the collector pressure, and the flow rate of each well was optimised without losses in total gas production for the group as a whole. The calculations demonstrated that, depending on the residual specific drainage volumes, three wells in the group were operated with insufficient gas flow rates: No. 1 – 7.8 thousand m^3/day (10.17 thousand m^3/day was required for optimal production), No. 3 – 4.49

thousand m³/day (6.63 thousand m³/day was required), and No. 6 – 1.52 thousand m³/day (1.82 thousand m³/day was required). The remaining wells demonstrated higher gas flow rates compared to the optimisation targets: No. 2 – 10.93 thousand m³/day (7.11 thousand m³/day was required), No. 4 – 5.06 thousand m³/day (4.41 thousand m³/day was required), and No. 5 – 4.55 thousand m³/day (4.2 thousand m³/day was required). Further research should be directed towards the study of well groups operating within a single gas pipeline that experience operational issues such as fluid accumulation at the bottom hole and bottom hole formation damage. These complications are most typical for gas and gas condensate wells and increasingly require novel approaches for their mitigation. The results obtained in this study can be applied in practice to establish efficient operating regimes for wells with different performance characteristics connected to a common collector.

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Оптимізація роботи групи свердловин із різними продуктивними характеристиками підключених у спільний колектор

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Анотація. Оптимізація експлуатації групи свердловин, підключених до одного трубопроводу, полягає у правильному розподілі напірного навантаження між свердловинами, що забезпечує відсутність втрат газовидобутку на рівні групи, а також максимальне залучення кожної свердловини до процесу видобутку. Тому метою дослідження було встановити оптимальний технологічний режим експлуатації свердловин, що враховує підключення свердловин у загальний колектор із різними робочими тисками на їх гирлі. Це можливо шляхом перерозподілу дебіту між свердловинами враховуючи запаси газу в питомому об'ємі дренування за рахунок встановлення на їх гирлі штуцера. Розв'язання задачі було досягнуто шляхом одночасного вирішення двох рівнянь: рівняння, що відображає сталість співвідношення між дебітом свердловини та запасами газу в одиниці об'єму дренування, і рівняння для об'ємної витрати газу під час адіабатного (тобто без теплообміну з навколишнім середовищем) протікання через штуцер, яке описувалось формулою Сен-Вена-Ванцеля. На основі розв'язання задачі та проведених обчислень встановлено, що три свердловини з групи експлуатувалися з заниженими дебітами, що зумовлено різницею у залишкових питомих об'ємах дренування, тоді як решта свердловин перевищували оптимальні параметри дебіту газу. Така невідповідність свідчить про нераціональне використання ресурсного потенціалу родовища. Запропоновано варіант розв'язання багатоцільової задачі, спрямований на оптимізацію технологічного режиму експлуатації групи свердловин та газозбірної мережі як єдиної інтегрованої системи видобування вуглеводнів. Реалізація даного підходу дозволяє досягти балансу між ефективністю відбору вуглеводнів і рівномірністю навантаження на інфраструктуру. Одержані результати дослідження будуть корисні на практиці для встановлення оптимальних технологічних режимів експлуатації свердловин із різними продуктивними характеристиками, які працюють в один колектор

Ключові слова: трубопровід; дебіт; штуцер; тиск; газ; родовище; система збору

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Research on the operation of a device for influencing the bottomhole zone of wells in depleted fields

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Abstract. The development of wells in the late stages of oil and gas field development is complicated by contamination of the bottomhole zone with process fluids due to a significant decrease in reservoir pressure. Existing methods of cleaning tubing or drill pipes to restore permeability are often ineffective due to the small volume of these pipes, the lack of measurements of the pressure drops generated, and the use of special equipment and maintenance services. Therefore, the aim was to study a device for influencing the bottomhole zone of the formation, which involves conducting suction not through tubing, but through a production string, measuring the magnitude of depressions-repressions, as well as the possibility of performing these works directly by the drilling crew. Theoretical, experimental and industrial research made it possible to create a device, the advantage of which is that its use makes it possible to significantly increase the magnitude of the depressions created, measure the depressions created, and record the curve of reservoir pressure recovery during swabbing. In addition, no additional equipment (geophysical drawworks, packer, etc.) was used except for that available to the drilling crew or overhaul crew. Dynamic stimulation of the well was achieved by creating hydrodynamic cyclic loads (depressions, repressions) on the bottomhole zone of the formation in order to clean it from contamination. The possibilities of creating cycles of depression-repression, their magnitude, and the loads that arise during swabbing were investigated. The possibility of conducting hydrodynamic studies in unstable modes with the removal of the pressure recovery curve directly during the swabbing process was proven. In addition, during the well development process, the device design provided for hydrodynamic studies. The device was successfully implemented at two wells in the Carpathian Region

Keywords: colmatage substances; well development device; swab; depression; repression; hydrodynamic studies of wells

Introduction

Swabbing is one of the most effective methods for inducing flow in wells with low reservoir pressure. At the present stage, technologies for cleaning tubing are used. These technologies are often ineffective because they create cycles with insufficiently high levels of repression-depression. In addition, they require the use of special equipment that is not available at production or drilling companies. Oil and gas wells that are coming out of drilling or after repair, especially in depleted fields with low reservoir pressure, are often very difficult to develop. This is due to pollution of the bottomhole zone and, as a result, a significant decrease in their productivity. In such cases, it is only possible to induce inflow after applying intensification methods, such as creating cyclic depressions in the formation by swabbing. In addition, hydrodynamic studies involving the descent of a deep-sea pressure gauge are necessary to

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determine the degree of contamination in the bottomhole zone. These works are associated with additional costs, loss of time and increased costs of the process.

One of the problems that arise during the development of wells in depleted fields after they have been drilled or repaired is contamination of the bottomhole zone and, as a result, a significant reduction in their productivity. Scientists S.V. Matkivskyi & L.I. Matiishyn (2023) analysed the impact of contamination of the bottomhole zone on the productivity of production wells. The authors assessed how different types of contamination (e.g., mechanical particles, petroleum products, chemical components) reduce formation permeability and decrease well flow rates. Based on the results of modelling and analysis of experimental data, a methodology for assessing the technical condition of the bottomhole zone was proposed and measures for its cleaning were recommended, which contributes to improving production indicators.

Modern methods of well development are often based on scientific principles and research that allow the use of advanced technologies to optimise production. For example, studying the impact of fluid accumulation in the wellbore is critical to understanding which fluid removal techniques are best suited to specific operating conditions. In their work, scientists A.V. Ugrynovskyi *et al.* (2024) considered innovative technological solutions for removing fluid from gas well bottoms, in particular the use of foaming surfactants. They describe the equipment and automated systems for supplying surfactants, and analyse their effectiveness using the example of wells in the Carpathian deposits. The results of the research indicate the feasibility of implementing such systems to improve the stability of flooded wells.

The method of swabbing was discussed in this article. The use of swabbing as a method of well development remains relevant due to its simplicity and effectiveness in conditions where other methods may be unavailable or ineffective, so scientific research and practical experience in this area continue to be valuable for the development of oil and gas fields (Maut *et al.*, 2024). It is a traditional method of well development used to reduce the fluid level in the wellbore, thereby creating a depression that promotes the flow of hydrocarbons from the reservoir. This method uses mechanical impact on the liquid string with the help of special equipment called a swab. A swab is a device that is lowered into a well on a rope or pipe and, when moving upwards, creates a vacuum behind it, which extracts fluid from the rock and lowers the fluid level in the wellbore. This allows the hydrostatic pressure in the well to be reduced, which is crucial for ensuring the flow of hydrocarbons (Jara *et al.*, 2024). Known devices and methods for developing oil or gas wells by swabbing, containing a piston, are used to reduce bottomhole pressure by moving the swab (piston) in the well. When moving upwards, the swab (piston) blocks 90% to 100% of the cross-sectional area of the well tubing, and when moving downwards, it allows 50% to 70% of the fluid flow to pass through the passage channels. The disadvantages of these devices and methods of well cleaning are insufficient hydrodynamic impact on the bottomhole zone of the formation, long duration of the operation, its high cost, and the need for special preparation of the wellhead and tubing string.

There are also known devices for developing oil and gas wells by swabbing, which involve lowering the fluid level by reciprocating movements of a stage plunger in the well, which moves in the tubing. The disadvantage of these devices is that they do not provide for the removal of the colmatant extracted from the formation, which can return to the formation during the reciprocating movements of the plunger (Khan *et al.*, 2023). An analysis of scientific literature has revealed key problems in modern swabbing operations: ineffective cycles of repression-depression, contamination of the formation's bottomhole zone, weak hydrodynamic impact, duration of operations, and the need for complex preparation of the wellhead and underground equipment. In response to these challenges, the device under investigation offers an innovative solution, aimed at creating a more efficient and cost-effective method of swabbing. This will significantly improve the development of complex wells, especially in depleted fields. The purpose of the article was to study the operation of a device for influencing the bottomhole zone of wells in depleted fields, which makes it possible to perform swabbing in the production string, induce flow, cleaning the bottomhole zone of the formation from colmatant, as well as conducting hydrodynamic studies in the process of swabbing during drilling or major repairs using only the equipment available at the well for lowering and lifting operations.

Materials and Methods

The diagram of the device, the operation of which was investigated in this article, is presented in Patent No. 135359 (2019) and I.M. Kuper & B.I. Mykhailyshyn (2023). To clarify the characteristics of the device, a prototype and a stand for modelling its operating modes were manufactured. The prototype was tested in two stages: the first stage involved using the prototype with a gap between the sealing unit and the casing string; the second stage involved using the prototype without a gap between the sealing unit and the casing string. During the tests, the following parameters were determined: time (speed) of lowering and lifting operations; axial force during lowering and lifting; volume of displaced fluid through the tubing string. Based on the layout and preliminary calculations, the design and sketches of the main components and the general appearance of the device were developed. During the work, experiments were also carried out and calculations of the structural elements of the device were refined, namely: research to determine the piston stroke required to compress the rubber cuffs to the specified size and the force required for such compression to ensure a specified clearance in the annular space when transferring the device from the transport position to the working position; calculations of the geometric characteristics of the hydraulic cylinder and piston depending on the pressure force required to move the device to the working position; calculations of the shear elements of the device based on the conditions of moving to the working position at the optimum pressure and its removal; calculations of the strength of the structural elements of the device.

To study the change in the diameter of sealing sleeves due to their compression, special templates were made for different sizes of production strings. The device was connected to a hydraulic press and pressure was created in the cavity of the device before the sealing sleeve touched the inner surface of the template of the corresponding diameter. The working characteristics must be determined for each set of sealing sleeves. Based on the results of strength calculations, requirements for materials and components, fits and roughness of mating surfaces, and requirements for the accuracy of their mutual positioning were developed. The hardness of surfaces subject to heat treatment and the requirements for coating individual parts are determined using the NOVOTEST TS-R stationary Rockwell hardness tester (Ukraine) is equipped with two indenters – a ball with a diameter of 1.5875 mm and a diamond cone pyramid with an angle of 120°, test loads of 60, 100 and 150 kg. For parts that come into direct contact with the inner surface of the casing string and are subjected to maximum loads during the descent of the device and its subsequent movement in the string during operation, special alloy steels with cementation of the outer layer and subsequent hardening to a hardness of HRC 52...56 were selected. This technology allows for high surface layer hardness with a plastic core, ensuring strength and wear resistance under alternating loads of maximum values.

When designing the seals for the sealing unit of the device, it was taken into account that the seal material must provide high hardness, tear resistance, as well as high relative elongation values and resistance to aggressive environments at temperatures up to 120 °C. At the same time, the cuffs should have a low percentage of residual deformation to facilitate removal and lifting of the device to the surface. A set of working drawings for the device was transferred to the Dolynska Repair and Production Base of the Public Joint Stock Company Ukrnafta (RBB PJSC Ukrnafta), and the manufacture of a prototype was organised. Design supervision and support for the manufacture of all components of the device were carried out (Fig. 1). Particular attention was paid to the design features and manufacturability of the hydraulic cylinder, piston and centring device. The production of spare parts kits, tools and accessories for the device was also organised (Fig. 2).

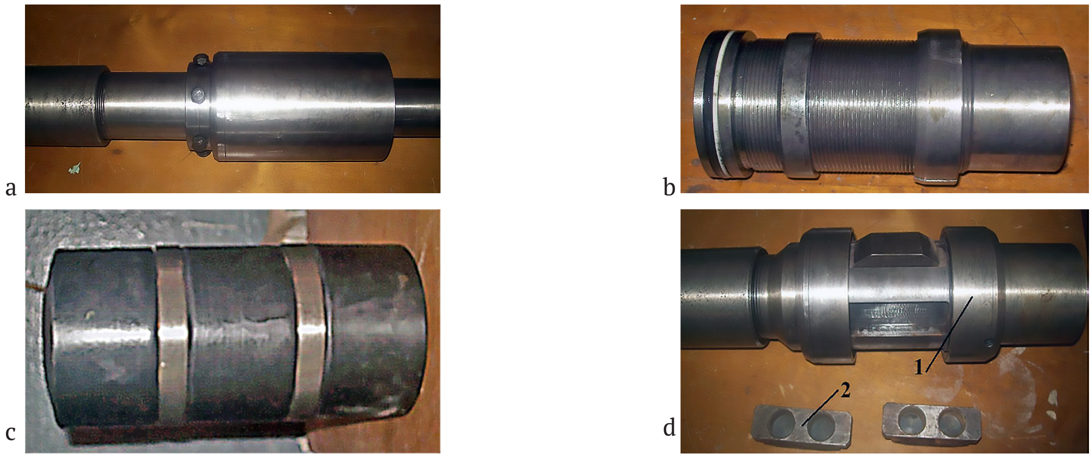

Figure 1. Components of the device

Note: a – device body with hydraulic cylinder; b – sealing sleeve diameter adjustment unit; c – sealing unit; d – centring device (1) with friction shoes (2)
Source: created by the authors

Figure 2. Set of spare parts for the device

Note: 1 – shear and locking screws; 2 – sealing and protective rings; 3 – shear saddles; 4, 5 – locking and limiting rings; 6 – templates for calibrating the outer diameter of sealing sleeves; 7 – special tool
Source: created by the authors

Preliminary tests were conducted on bench equipment in the laboratory (Fig. 3).

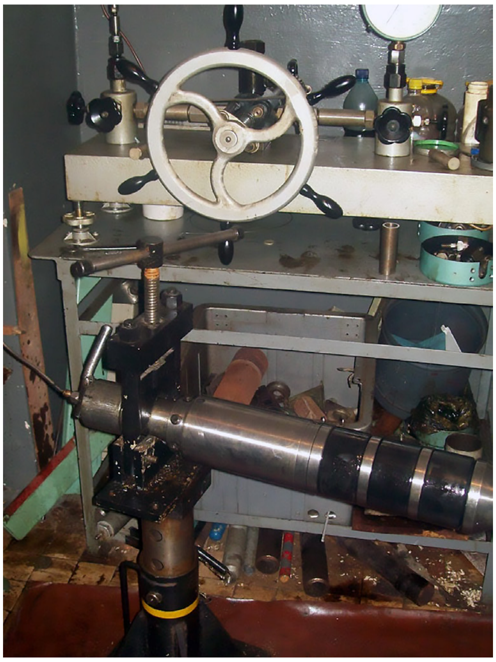

Figure 3. Preliminary testing of the device on a test bench
Source: created by the authors

The tests were conducted by creating pressure in the device cavity. Under pressure, the piston begins to move in the hydraulic cylinder, compressing the rubber sleeves to a specified diameter depending on the inner diameter of the production string and the required clearance between the string wall and the device. In the working position, the piston and cuffs were fixed by a locking device. The piston stroke and, accordingly, the diameter of the cuffs in the working position are adjusted using a special limiter. During testing, a series of cycles were performed to bring the device into working condition at different limiter positions, and the parameters and characteristics necessary for its adjustment before use on production strings of different internal diameters were determined.

Based on the data obtained, the operating characteristics of the device were determined for two sets of sealing sleeves for production tubing with diameters of 146 and 168 mm. After manufacturing and adjusting the device for a production string diameter of 146 mm and bringing it to working condition, experimental industrial tests were conducted. The purpose of the tests was to check the functioning and study the operating parameters of the device under various operating modes in real operating conditions. The technical characteristics of the prototype device for influencing the bottomhole zone of wells are given in Table 1.

Table 1. Main technical characteristics of the device

Technical characteristics	Numeric value
Diameter of the production string in which the device can be used, mm	146
Wall thickness of the production string, mm	from 6.5 to 10.7
Range of sealing unit diameter settings, mm	from 118 to 133
Pressure required to put the device into working position, MPa	10
Shear pressure of the valve assembly seat before lifting the device from the well, MPa	from 20 to 25
Principle of switching to working position	hydraulic
Overall dimensions, mm: ◈ outer diameter of the body ◈ outer diameter of the centraliser ◈ length	 118 140 1,515
Connection thread to the string TUBING GOST 633-80	73

Source: created by the authors

The first experimental industrial tests of the device were conducted to determine its performance and debug all its components in industrial conditions. In this regard, wells 2-Monastyrchany and 811 Pasichna, which had been inactive for a long time and in which no significant increase in flow rate could be expected as a result of the work, were used as test objects. The design of the 2-Monastyrchany well is as follows: a 324 mm conductor was lowered to a depth of 705 m and cemented to the well bottom. The 245 mm technical string was lowered to a depth of 4,221 m and cemented to the bottom. The 146 mm production string was lowered to a depth of 4,221 m and cemented to the bottom. The string was pressurised to 40.7 MPa. Steel grade of pipes for production strings D and E, wall thickness 9.5…10.7 mm. The drilled bottomhole depth was 4,221 m, and the artificial bottomhole depth was 3,850 m. The perforation interval was within the range of 3,603-4,221 m. The reservoir pressure was 19.2 MPa.

The production string was tested using a template with a diameter of 118 mm and a length of 2.5 m to a depth of 3,350 m. After that, a device with a Ukrainian-made AMT depth pressure gauge, a KTSZ-102-60M circulation valve and a pressure test saddle on an equal-strength tubing string with a diameter of 73 mm and a strength group of at least No. 80 was lowered into the well to a depth of 3,300 m. During lowering, the tubing was checked using a 59 mm diameter template. The lowered tubing string was pressure tested at 25 MPa. The bottomhole pressure at the installation site was 18.7 MPa, and the temperature was 87 °C. The weight of the tubing string before the start of testing was 28.5 tonnes.

The tests were conducted using the A-50 lifting unit. The pressure testing of the tubing, the transfer of the device from transport mode to working mode, and the cutting of the saddle were carried out using a CA-320 pump unit from the Kremenchug Automobile Plant. A tank with a total volume of 30 m^3 and a tanker truck were used to collect the fluid pumped out of the well. The wellhead was connected according to the diagram shown in Patent No. 135359 (2019) and in I.M. Kuper & B.I. Mykhailyshyn (2023). The swivel hose was inserted into the container. The tests were conducted in two stages: the first stage involved cyclical movement of the device in the production string with 40-second stops at the upper and lower points, and the second stage involved movement without such stops.

The device was also tested in well 811-Pasichna. The well design was as follows: a 324 mm conductor was lowered to a depth of 1,838 m and cemented to the bottom. The 245 mm technical string was lowered to a depth of 3,610 m and cemented to the bottom. The 168 mm production string was lowered to a depth of 1,901 m, and the 146 mm string was lowered to a depth of 1,901-3,970.29 m and cemented to the bottom. The string was pressure tested at 28.9 MPa. The steel grade of the production string pipes is D, E and K with a wall thickness of 8.9...10.7 mm. The drilled bottomhole depth was 4,400 m, and the artificial bottomhole depth was 3,970 m. Current state of the bottomhole: head of emergency tubing 73 – 3,661.3 m. The perforation interval is within 3,895-3,897 m. Reservoir pressure is 47.8 MPa at a depth of 3,960 m. The production string was cased with a 118 mm diameter and 2.5 m long casing to a depth of 3,350 m. After that, device -146 with an AMT depth pressure gauge, a KTSZ-102-60M circulation valve and a pressure testing saddle on an equal-strength tubing string with a diameter of 73 mm and a strength group of at least No. 80 was lowered into the well to a depth of 3,300 m. During lowering, the tubing was calibrated using a 59 mm diameter template. The lowered tubing string was pressure tested at 25 MPa. The bottomhole pressure at the installation site was 18.7 MPa, and the temperature was 87 °C. The weight of the tubing string before the start of testing was 28.5 tonnes. Work on the development of technical documentation, manufacture and implementation of a device for the development and exploration of wells was carried out at the Research and Design Institute of PJSC Ukrnafta (RDI PJSC Ukrnafta).

Results and Discussion

The results of studies to determine the piston stroke required to compress rubber cuffs to a specified size are shown in Table 2 and Figure 4.

Table 2. Research to determine the piston stroke required to compress rubber cuffs to a specified size

Casing string size	Inner diameter of the template, mm	Working stroke of the piston, mm (cuff set No. 1)	Working stroke of the piston, mm (cuff set No. 2)	Operating pressure, MPA
146 × 10.7	124.6	23	29	3.0
146 × 9.5	127	30	35	4.2
146 × 8.5	129	35	39	4.2
146 × 7.7	130.6	38	43	4.8
146 × 7.0	132	42	47	4.8

Source: created by the authors

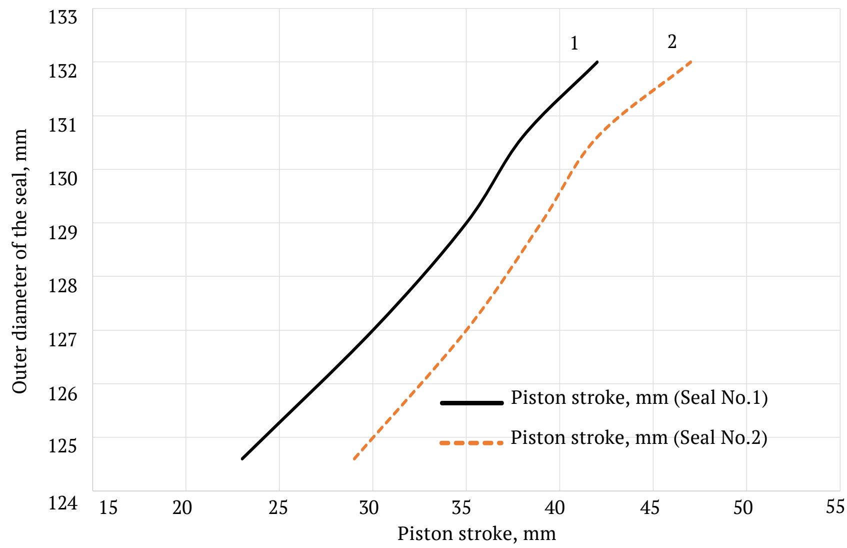

Figure 4. Dependence of the diameter of the sealing cuff of device -146 on the piston stroke with a pusher

Source: created by the authors

Taking into account the relevant calculations and preliminary design of components and parts, the configuration of the dimensions of each part and the design as a whole was refined. The geometric characteristics and main dimensions of the device components were determined. Table 3 shows the results of calculations of the axial force that arises during the operation of the device. The 2-Monastyrychany well was put into operation in 1991 with an initial gas flow rate of 150,000 m^3/day and condensate flow rate of 17 t/day. The initial reservoir pressure was 49.8 MPa. During 1991-1993, gas production declined significantly to 30,000 m^3/day and remained at this level until 2002. In 2003-2005, gas flow ranged from 17 to 9 thousand m^3/day at operating pressures of 3.5/7.0 MPa. During the first year of operation of the well, there was a sharp drop in reservoir pressure from 49.8 to 31.4 MPa, i.e. to the average for the deposit. Subsequently, with a decrease in withdrawals, the pressure decline slowed down somewhat, with the pressure measured in 2007 standing at 23 MPa.

Table 3. Calculation of loads during device operation using a typical well with averaged data as an example

Inner diameter of the well	m	0.126
Outer diameter of drill pipes	m	0.073
Drill pipe wall thickness	m	0.007
Swabbing depth	m	3,000
Liquid density	kg/m^3	1,000
Pipe material density	kg/m^3	7,850
Calculation results		
Pipe weight	kg	34,163.5
Annular space volume	m^3	24.838
Mass of the liquid in the annular space	kg	24,838.2
Volume of liquid in pipes	m^3	8.198
Mass of liquid in pipes	kg	8,197.76
Extra weight (from swab friction)	kg	200
Total weight on the hook	kg	67,399.5
Hook load	kN	661.19
Pipe area	m^2	0.00145
Pipe stresses	MPa	455.31

Source: created by the authors

The test results are shown in Table 4. As a result of the tests conducted on the release device, its performance in various operating modes was analysed. A total of 36 cycles were performed, each consisting of the device operating in two directions – up and down. At different stages of testing, the length of the working stroke varied and was 4 or 8 metres. At the same time, the number of cycles in the series varied from 5 to 15, which indicates the possibility of adjusting the swab operating mode depending on the specific conditions of the well.

Table 4. Results of testing device -146 in well 2-Monastyrchany

Stages of work	Start of the stage, h., min.	Working stroke of the device, m	Number of cycles	Lifting force on the hook without taking into account the weight of the tubing string, ts	Average lifting speed, m/s	Unloading of the tubing string during lowering, ts	Average lowering speed, m/s	Maxi mum depression, MPa	Maxi mum repression, MPa
1. Addition of 3.8 m^3 of formation water to the tubing string to a pressure of 1 MPa (device landing)	12. 32	-	-	-	-	-	-	-	-
2. Cyclical movements of the device in the production string (with 40-second stops at the upper and lower points)	12. 50	4	5	5.8	0.13	4.8	0.13	5	2.1
	13. 05	8	5	6.3	0.13	12.7	0.13	5.7	5.7
3. Cyclical movements of the device in the production string (without stopping at the upper and lower points)	13. 22	8	15	7.6	0.18	4.9	0.40	9.0	5.4
4. Stop to stabilise pressure	13. 35	-	-	-	-	-	-	-	-
5. Cyclical movements of the device in the production string (without stopping at the upper and lower points)	14. 28	8	15	8.0	0.20	6.7	0.50	8.7	5.6
6. Cyclical movements of the device in the production string (with 40-second stops at the upper and lower points)	14. 42	8	5	7.1	0.13	7.7	0.26	8.9	6.1
7. Stop to stabilise pressure	14. 55	-	-	-	-	-	-	-	-
8. Addition of 0.41 m^3 of formation water to the tubing string to a pressure of 8 MPa (circulation valve pin cut)	15. 15	-	-	-	-	-	-	-	-
9. Lifting the device from the well	15. 54	-	-	-	-	-	-	-	-

Source: created by the authors

During the analysis of the device's speed characteristics, it was found that its average upward speed varied between 0.13 and 0.20 m/s, and its downward speed varied between 0.13 and 0.50 m/s. An increase in lowering speed to 0.50 m/s may be associated with a reduction in hydraulic resistance when lowering the swab. At the same time, such variability in the speed regime is an important factor affecting the efficiency of the drilling process, as it determines the dynamics of pressure changes in the well. Analysis of the forces acting on the device hook made it possible to assess the load on the swab and the characteristics of fluid lifting. When moving upwards, the force varied from 5.8 to 8.0 tf, indicating variable hydraulic resistance. During downward movement, unloading occurred, ranging from 4.8 to 12.7 ts. Such an increase in force load during the lowering of the swab may be associated with the peculiarities of fluid movement in the well, as well as with possible hydrodynamic effects affecting the process of unloading the fluid column.

An important indicator of the effectiveness of the swab is the depression created on the formation, which was recorded using a depth manometer. It varied between 5.0 and 9.0 MPa, indicating a significant reduction in reservoir pressure and the potential for intensified hydrocarbon inflow into the well. At the same time, the significance of the repressions that arose during the lowering of the swab ranged from 2.1 to 6.1 MPa. High repression values may indicate a temporary decrease in fluid inflow due to the effect of pumping fluid back into the formation, which requires optimisation of the swabbing parameters.

Variation of the device speed over a wide range allows the process to be adapted to different hydrodynamic conditions. The maximum force on the hook when lifting up to 8.0 tonnes indicates the device's ability to operate under conditions of significant hydraulic resistance. High values of repression during downward movement can negatively affect pumping efficiency, requiring adjustment of the speed mode. Optimisation of the device's motion control algorithm minimises the negative impact of repressive processes and ensures a stable flow of fluid. Thus, the test results confirm the effectiveness of swabbing as a method of intensifying inflow and indicate the need for further research on optimising the device's operating modes. During the tests, pressure changes were recorded over time using a pressure gauge located below the device. This entry is shown in Figure 5.

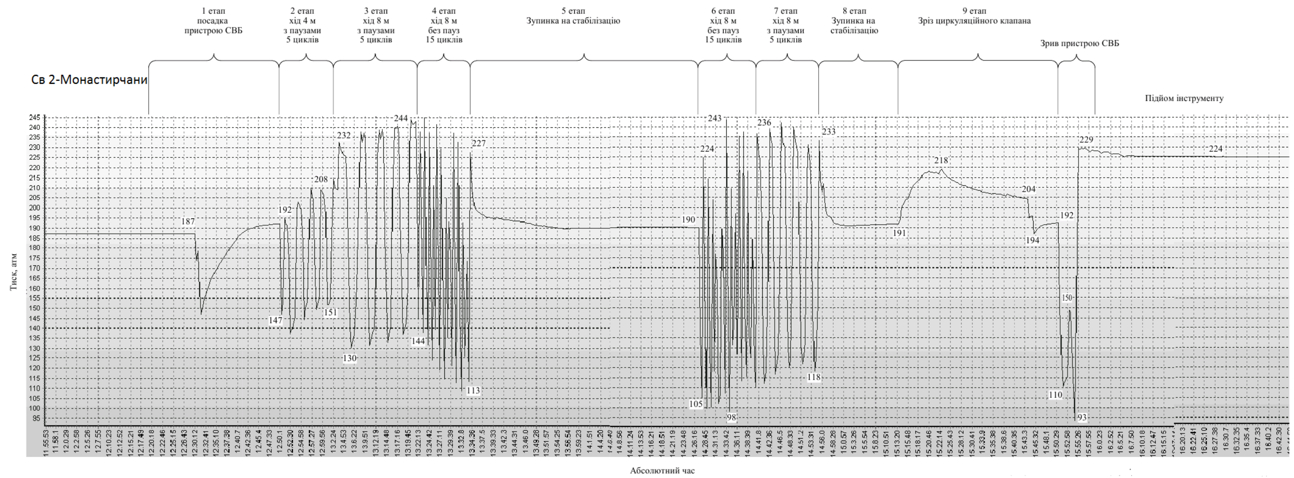

Figure 5. Recording of pressure changes over time using a depth manometer during experimental industrial testing of device -146 in well 2-Monastyrchany

Source: created by the authors

Processing the pressure change curve during the creation of depression-repression cycles makes it possible to establish the filtration characteristics of the formation and their changes as a result of the work carried out. In fact, the recovery curves of reservoir pressure were recorded in each cycle of depression-repression creation. The results of the device testing were similar to those obtained in the 2-Monastyrchany well. Effective well development methods depend on creating a depression, which is the process of reducing the pressure inside the well to a level below the formation pressure. This can be achieved by several methods: replacing the fluid in the well with a fluid of lower density, aerating the fluid, or using gas cushions, instantaneous depression methods, deep pumps, swabs, buckets, jet devices, and capillary systems. Each of these methods has its own characteristics and can be selected depending on the specific characteristics of the well and the formation. Researchers Y.A. Shumakov *et al.* (2022) analysed practical approaches to solving flow assurance problems during testing and cleaning of gas wells.

This is especially true for wells located in depleted fields with low reservoir pressures. The development of such wells requires the search for effective methods of influencing the bottomhole zone, inducing inflow, and conducting hydrodynamic studies. The article by O.G. Semenyaka *et al.* (2019) discussed the modern approach to the operation of wells with reduced reservoir pressure, which requires the implementation of new technical solutions. The aim of their research was to experimentally evaluate the technology for developing wells at the final stage of their development, with an emphasis on selecting the optimal technical approach for extracting reservoir fluid under low pressure conditions. The implementation methodology involves the use of innovative equipment that allows foam to be generated for the purpose of cleaning the bottomhole and wellbore. Future research into the device could consider the use of reagents that form foam.

Another important aspect is development after hydraulic fracturing, as noted by R. Shidhani *et al*. (2022). According to M.A. Myslyuk & V.P. Kravets (2024), well development within the West Khrestishchensky field is carried out immediately after hydraulic fracturing, which increases the efficiency of hydrocarbon flow from productive horizons. Industrial results of development were systematised based on actual data, including examples of successful flow recovery after propant injection. Correlation analysis has established statistically significant relationships between hydraulic fracturing technology parameters and well development efficiency, confirming the feasibility of an integrated approach to well completion and commissioning. The device under study should be used after hydraulic fracturing of the formation for rapid development of the well.

Such technological processes are usually performed separately from each other. At the same time, service production facilities, additional service personnel and technological and transport equipment are involved. All this leads to a significant increase in the cost of well development and exploration. This is discussed in the article by X. Zheng *et al*. (2022). The authors analysed the current challenges facing oil and gas production engineering, including the increasing complexity of technologies, insufficient progress in digital transformation, and the lack of key technical support for energy conservation and emissions reduction. Swab combines several technological processes that significantly reduce the cost of the work performed. Numerous variations and improvements in swabbing are described in the scientific literature. An analysis of the articles was conducted in comparison with the research device. In the article by J. Zhu *et al*. (2019), which reflects the non-stationary processes of plunger operation in gas wells, the authors focused on accurately predicting the dynamics of fluid and gas interaction under variable pressure conditions. However, unlike a computer model, which is mainly used for analytical or simulation planning, the device under study implements the physical creation of depression and repression cycles in real well conditions with simultaneous recording of hydrodynamic characteristics, which is advantageous in an operational environment where unpredictable factors often reduce the effectiveness of preliminary calculations.

Scientists Z. Zhang *et al*. (2022) described the impact of swabbing on long-term well productivity. In particular, the results show that incorrect or excessive drilling can lead to contamination of the formation and a reduction in its permeability due to mechanical damage to the rock. This is confirmed by the significant levels of repression recorded during the swab studies. In this context, the developed device is distinguished by its ability to precisely regulate the speed of movement, which allows limiting the amount of repression and avoiding exceeding critical loads on the formation structure. Scientists A. Mohammad & R. Davidrajuh (2022) described that the effectiveness of swabbing can vary significantly depending on the specifics of the well and the characteristics of the formation. An important aspect is choosing the right type of swab and its size, which best matches the diameter of the well and the physical properties of the extracted fluids. The research demonstrated a significant influence of the working stroke length on the force and speed of the device. This indicates the need to select the optimal drilling parameters for each specific well, taking into account its hydrodynamic characteristics. Compared to their recommendations for modelling, the device under study already integrates on-site pressure measurement capabilities thanks to a built-in depth manometer, which allows theoretical hypotheses to be tested in practice in real time.

Researchers N. Seymour *et al*. (2023) examined the problem of 'swabbing' in wells, which occurs due to deformation and blockage of the annular space by the seal, causing significant delays and costs. To address this issue, the authors developed and validated a predictive numerical model that simulates the physical basis of the swabbing effect and helps optimise seal design. The model was verified through physical testing and demonstrated high accuracy in predicting flow velocity, enabling engineering teams to effectively identify swabbing risks and improve seal designs to increase their resistance. The numerical model can be integrated into the device under investigation to improve the design of the device seal. Another aspect that is important to consider when drilling is the temperature of the fluid in the well, as noted in the work of M. Khaled *et al*. (2023). In this regard, it is important to emphasise that special heat-resistant materials were selected for the seals and working components of the device under study, capable of functioning at temperatures up to 120 °C, as confirmed by tests in wells with temperatures up to 87 °C. X. Luo *et al*. (2019) in their review of vortex instruments for fluid extraction emphasised the prospects for automation and continuous process control. At the same time, the practical application of such systems requires complex infrastructure, which has been avoided in the developed device – autonomy and compatibility with basic drilling equipment are significant advantages in cases of limited technical support.

Swab testing, as a method of well development, is used not only for practical purposes to increase well productivity, but also as a means of conducting geological and petrophysical studies. Scientist J. Gagnon (2023) wrote that it can provide important information about the characteristics of the formation, such as permeability, porosity, and the presence of certain deposits in the pores. During the drilling process, when fluid is extracted from the well, a depression is created, causing fluids from the formation to move towards the well. This makes it possible to investigate how easily fluid penetrates through the formation, which is a direct indicator of its permeability. The data obtained during the research on changes in depression within the range of 5.0-9.0 MPa allows to conclude that suction can be used not only as a means of extracting fluid, but also as a tool for assessing reservoir characteristics. Research by S. Abbasova & S. Abbaszade (2023) demonstrates how analysis of data on fluid extraction rate and pressure generated can be used to assess these petrophysical properties of the formation. Similar observations were made during experimental tests, when changes in the speed of the swab affected the level of depression created. This confirms the conclusions about the possibility of using swab testing as a method for diagnosing reservoir conditions and determining the effectiveness of fluid penetration into the well.

Swabbing is also used to assess the condition of wells, in particular to identify areas of colmatage. Colmatation can significantly reduce well efficiency by reducing oil or gas flow. The use of swabbing allows you to identify areas where there is a significant drop in pressure, indicating possible areas of colmatation. Research by C. Liao *et al*. (2023) presented methods for interpreting swabbing data to identify these critical zones. Experimental studies have observed significant unloading during downward movement, which may indicate the presence of zones with increased fluid resistance or reduced permeability at certain intervals of the well. This confirms the possibility of using swab data to assess the condition of the formation and identify problem areas in the well.

In summary, these studies not only help to optimise the use of swabbing in practice, but also provide a deeper understanding of the processes occurring in wells and ways to control them and minimise potential risks. Swabbing is an effective method not only for stimulating fluid flow, but also for conducting geological, petrophysical and diagnostic studies of wells. The advantage of the device under study is that its use does not require additional equipment (compressor, pump unit, geophysical drawworks, packer, etc.) other than that available to the drilling crew or overhaul crew. Dynamic stimulation of the well is achieved by creating hydrodynamic cyclic loads (depressions, repressions) on the bottomhole zone of the formation in order to clean it from colmatant. In addition, during the well development process, the device design provides for hydrodynamic studies. The device can be used for well development as well as for influencing the bottomhole zone of the formation before or after hydraulic fracturing, acid treatment, treatment with surface-active substances, etc., for the purpose of preliminary cleaning of the bottomhole zone.

Conclusions

The operation of a device for influencing the bottomhole zone of wells was investigated. Bench and industrial tests proved the possibility of swabbing a well directly in the production string and conducting hydrodynamic studies directly during the swabbing process. Based on the results of these studies, a device was designed and manufactured, and tested in the 2-Monastyrchany and 811-Pasichna wells. The possibility of drilling a well using a drilling rig or lifting unit was proven.

The depression created in the formation, which was recorded using a depth manometer built into the device, varied between 5.0 and 9.0 MPa, indicating a significant reduction in bottomhole pressure and the potential for intensified hydrocarbon flow into the well. At the same time, the significance of the repressions that arose during the lowering of the swab ranged from 2.1 to 6.1 MPa. Analysis of the forces acting on the hook during operation of the device made it possible to assess the load on the swab and the characteristics of fluid lifting. When moving upwards, the force varied from 5.8 to 8.0 tf, indicating variable hydraulic resistance. During downward movement, unloading occurred, ranging from 4.8 to 12.7 ts. Such an increase in force load when lowering the swab is associated with the peculiarities of fluid movement in the well, as well as with possible hydrodynamic effects.

Variation of the device speed over a wide range allows the process to be adapted to different hydrodynamic conditions. The maximum force on the hook when lifting up to 8.0 tonnes indicates the device's ability to operate under conditions of significant hydraulic resistance. Adjusting the speed of the device allows you to change the values of depression and repression on the layer. The results of experimental industrial tests in the well confirmed the operability and efficiency of the device in creating a hydrodynamic effect (cycles of depressions and repressions) on the bottomhole zone of the formation. The possibility of conducting hydrodynamic studies during the use of the device was also successfully tested. In the future, it is planned to investigate the operation of the device in combination with other intensification methods.

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Conflict of Interest

None.

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Дослідження роботи пристрою для впливу на привибійну зону свердловин виснажених родовищ

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Анотація. Освоєння свердловин на пізній стадії розробки нафтових і газових родовищ ускладнено забрудненням привибійної зони технологічними рідинами в зв'язку зі значним зменшенням пластового тиску. Існуючі методи свабування в насосно-компресорних чи бурових колонах труб для відновлення проникності часто виявляються малоефективними з причини малого об'єму цих труб, відсутності замірів створюваних перепадів тиску та використання спеціального обладнання і сервісного обслуговування. Тому метою було дослідження пристрою для впливу на привибійну зону пласта, які передбачають проведення свабування не через колону насосно-компресорних труб, а через експлуатаційну колону, вимірювання величини депресій-репресій, а також можливості виконання цих робіт безпосередньо буровою бригадою. Проведені теоретичні, експериментальні й промислові дослідження дали можливість створити пристрій, перевагою якого є те, що його використання дає можливість суттєво збільшити величину створюваних депресій, проводити замір створюваних депресій, знімати криву відновлення пластового тиску під час свабування. Окрім того не застосовується додаткова техніка (геофізична лебідка, пакер тощо) окрім тієї, яка є в розпорядженні бригади бурової чи бригади капітального ремонту. Динамічне збудження свердловини досягається створенням гідродинамічних циклічних навантажень (депресій, репресій) на привибійну зону пласта з метою очищення її від забруднень. Було досліджено можливості створюваних циклів депресій-репресій, їх величини, а також навантажень, які виникають під час проведення свабування. Доведено можливість проведення гідродинамічних досліджень на неусталених режимах зі зняттям кривої відновлення тиску безпосередньо в процесі проведення свабування. Окрім того, у процесі освоєння свердловини конструкція пристрою передбачає проведення гідродинамічних досліджень. Пристрій успішно впроваджений на двох свердловинах родовищ Прикарпаття

Ключові слова: кольматуючі речовини; пристрій освоєння свердловин; сваб; депресія; репресія; гідродинамічні дослідження свердловин

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Analysis of technical solutions for ensuring the safety of pipeline gas transport at large industrial facilities

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Abstract. The purpose of the study was to improve the reliability and safety of gas pipeline operation through a detailed analysis of modern technical solutions, innovative technologies, and effective control methods. Modern technical and organisational solutions for ensuring the safety of pipeline gas transport at industrial facilities were analysed. It was established that the highest efficiency is demonstrated by the combination of automated control systems, the use of corrosion-resistant materials, and network segmentation using emergency valves. The technical characteristics of the main pipe materials were analysed: in particular, austenitic stainless steel can withstand up to 2.5 megapascals at a temperature of +120°C, which makes it suitable for main gas pipelines; polyethene (PE100) provides operation at a pressure of up to 1.0 megapascals and a temperature of +40°C, which is suitable for underground gas supply. Sensor types were also considered, in particular, methane gas analysers with an accuracy of ±2 particles per million and a reaction time of up to 5 seconds, which is especially effective for polymer pipes. The article summarised the experience of using intelligent devices for in-tube diagnostics that can detect mechanical defects without stopping transportation. Special attention was paid to the use of unmanned aerial vehicles: multicopters with thermal imagers and cruise drones with a laser scanner allow quickly examining hard-to-reach areas up to 50 km long. It was concluded that it is necessary to integrate these solutions into a comprehensive maintenance system. The results obtained can be used to develop and implement modern integrated safety systems at industrial facilities, which will help reduce accidents and improve the reliability of gas transmission infrastructure

Keywords: monitoring; diagnostics; leakage; corrosion; automation; innovation

Introduction

Pipeline transport is a key element of the infrastructure of large industrial facilities, ensuring a continuous supply of natural gas for production needs. However, the operation of such systems is associated with increased risks, including gas leaks, explosions, fires, and environmental pollution. The issue of safety is becoming particularly relevant in the context of the increasing technological complexity of facilities and tougher environmental requirements. Traditional methods of pipeline control and maintenance are gradually being supplemented or replaced by modern technical solutions based on automation, digital technologies, and innovative materials. In this context, there is a need for a systematic analysis of the effectiveness of such solutions, considering the practical needs of industrial enterprises.

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Timely detection and elimination of emergencies, such as gas leaks, corrosion and mechanical damage to pipelines, is an important issue in ensuring the safety of pipeline gas transport at large industrial facilities. L. Kutsenko *et al*. (2023) emphasised the importance of automating control processes to improve maintenance efficiency. Investing in these technologies helps reduce the risk of accidents and simplifies the monitoring of pipeline condition. M. Waqas & M. Jamil (2024) pointed out the advantages of using Supervisory Control and Data Acquisition (SCADA) systems, which provide remote monitoring and control over all parameters of gas pipelines. This allows quick detection of anomalies and prevents serious accidents. J. Yao *et al*. (2022) stressed the importance of using intelligent pigs for intra-tube diagnostics, which allows detecting defects at an early stage. Such a system enables the timely detection of corrosion zones and mechanical damage to pipelines. I.A. Aromoye *et al*. (2025) noted that the use of drones for pipeline inspections allows inspections to be conducted in hard-to-reach places without risking the lives of personnel. This greatly increased the efficiency of maintenance and reduced labour costs. J. Zishu *et al*. (2025) drew attention to the need to use anticorrosive materials to extend the service life of gas pipelines. The choice of such materials has reduced the likelihood of leaks and other problems associated with pipe wear.

S.F. Pichugin *et al*. (2023) underlined the importance of implementing emergency shut-off systems to quickly shut off gas flow during an accident. This has helped prevent escalating emergencies and reduce risks to the environment and workers. A.H.A. Nasser *et al*. (2021) accentuated the importance of training personnel for effective emergency management. A high level of training of employees is critical for ensuring safety at all stages of gas pipeline operation. G. Fidalgo-Valverde *et al*. (2024) recommended the use of degassing and gas extraction technologies to minimise the environmental risks associated with gas leaks. These methods provide for a timely reduction of the gas concentration in the atmosphere, preventing explosions and environmental pollution. J.S. Ahari *et al*. (2025) proposed the installation of flare combustion systems for the safe disposal of excess gases. This made it possible to avoid explosive situations and ensure effective management of excess gas. D. Bęben & T. Steliga (2023) underscored the importance of regular monitoring and diagnostics of pipelines to detect problems in a timely manner and prevent accidents. Continuous monitoring is the basis for the safe operation of gas pipelines.

However, despite numerous achievements, there are gaps in research that require further study. This includes a more detailed analysis of combined systems to ensure safety, integrating the latest technologies into real-world production conditions, and developing new methods to minimise environmental risks associated with gas leaks. The issues of adapting technologies to various climatic and geographical features and the development of effective methods of teaching and training personnel to work with new systems remain insufficiently researched. The study aimed to evaluate modern design, engineering, and organisational solutions for ensuring the safety of pipelines, particularly through the improvement of materials, control systems, accident prevention tools and innovative approaches for large industrial facilities. Research objectives: review of the effectiveness of using the latest materials and technologies to ensure the reliability of pipelines, evaluation of monitoring and control systems, in particular, SCADA systems and leak sensors, and research of innovative approaches, such as the use of IoT sensors, artificial intelligence-based analytics (AI-analytics), and drones for inspections.

Materials and Methods

The study conducted a comprehensive analysis of technical solutions aimed at improving the safety of pipeline gas transport at large industrial facilities. In the field of structural solutions, the use of anticorrosive materials, in particular, stainless steel and composite coatings, which ensure the resistance of pipelines to aggressive environments and extend their service life, was analysed. The expediency of using polymer pipes for internal networks within the limits of regulatory restrictions was investigated. The effectiveness of modern connection methods, such as automated welding using non-destructive testing, as well as flanged connections that can withstand high pressure, was evaluated. Considerable attention was paid to the division of pipeline systems into segments with insulating valves and the use of bypasses in critical areas – as a means of improving maintainability and rapid response to emergencies.

In terms of control and monitoring, the use of SCADA systems that provide remote equipment management and operational collection of telemetry data was analysed (Eso & Eseosa, 2022). The possibilities of detecting leaks using methane, pressure and noise sensors, as well as mass flow balancing methods that allow rapid localisation of hazardous areas, were investigated. The use of video surveillance and thermal imagers that help detect extraneous interference or overheating of equipment is considered. In the direction of emergency response solutions, the effectiveness of emergency shutdown systems that automatically block the gas flow in case of exceeding the permissible parameters was investigated. The paper analyses the use of degassing systems, in particular, ventilation equipment and flare gas combustion, as well as fire protection measures – including flame extinguishers, fire-fighting valves, and fire-resistant pipe coatings.

The study pays special attention to organisational and technical security measures. The effectiveness of scheduled licensing inspections, which allow timely detection of critical wear and tear and violations, is considered. The use of intelligent devices for in-tube diagnostics, in particular, pigs, capable of detecting corrosion, cracks, and mechanical defects without stopping transportation, is analysed in detail. Attention is paid to the training of personnel – in particular, training in responding to accidents and working with modern monitoring systems. The impact of implementing the standards ISO 14001:2015 (2015), ISO 45001:2018 (2018), and EN 15001-1:2023 (2023) on improving the level of technological and environmental safety was also assessed.

Lastly, the study covered innovative technologies – the use of IoT sensors, digital doubles, artificial intelligence-based analytics, and drones for inspections of hard-to-reach areas. The theoretical potential of using the latest technologies to improve the efficiency of pipeline inspections and emergency detection was considered. In particular, the possibilities of aerial photography and detection of temperature anomalies were analysed using a DJI Matrice multicopter equipped with a 4K camera and a FLIR thermal imager. The use of the eBee X cruise drone for terrain scanning and external risk assessment, which has Light Detection and Ranging (LIDAR), Global Positioning System (GPS), and an RGB camera, was also evaluated. The use of a hybrid WingtraOne equipped with a CH_4 gas analyser and a thermal scanner was reviewed to detect gas leaks. These technologies were explored in terms of their ability to integrate into existing infrastructure with minimal interference, allowing for early detection of system deviations and accident prevention.

Results

The choice of materials for pipelines is one of the most important aspects in the engineering of gas supply systems, as it determines their durability, resistance to aggressive environments, and ability to withstand high loads. Modern pipelines use a variety of materials that meet the highest safety and efficiency standards (Table 1).

Table 1. Comparison of pipeline materials

Material	Corrosion resistance	Max. working pressure (MPA)	Temperature limit (°C)	Main application
Austenitic stainless steel	High	2.5	+120	Main gas pipelines, compressor stations
Aluminium composite	High	1.6	+95	Distribution networks, internal networks
Polyethene (PE100)	High	1.0	+40	Underground gas supply, medium pressure
Polypropylene (PP-R)	Medium	1.6	+70	Domestic and industrial pipelines

Source: compiled by the authors based on I.M. Chohan *et al*. (2023)

One of these solutions is anticorrosive alloys and coatings, including austenitic stainless steels, aluminium composites and multilayer polymer materials. Austenitic stainless steels, due to their high corrosion resistance and ability to withstand extreme temperatures, are optimal for use in aggressive environments. These alloys ensure a long service life of pipelines, minimising the risks of intergranular corrosion, which can lead to structural destruction. Aluminium composites, due to their lightness and high corrosion resistance, are used in less aggressive conditions, such as external coatings of pipelines exposed to atmospheric factors. Thereby, polymer materials, in particular, polyethene (PE) and polypropylene (PP-R), are used for internal gas pipelines that are subject to less mechanical loads, but require excellent resistance to chemical influences and water corrosion. Such materials that meet the modern requirements of State Building Codes can notably reduce maintenance costs and increase the reliability of gas supply (Gharbia *et al*., 2022). In addition, pipelines designed for increased operating loads must withstand high internal pressure of more than 1.6 MPA and temperature fluctuations up to +120°C. These characteristics are especially important for gas pipelines operating under high-pressure conditions or transporting gas that has an elevated temperature. Therefore, pipelines must have high strength characteristics and the ability to operate for a long time under variable loads (Topolski *et al*., 2022). The reliability of connections is a critical aspect for ensuring the tightness and safety of pipelines. Traditional connection methods, such as welding and flanging, should be optimised for each specific case, accounting for the operating conditions and safety requirements (Zeng *et al*., 2021).

For pipeline welding, automated welding complexes are used, which are equipped with non-destructive testing systems, such as ultrasonic flaw detection and radiography. This guarantees the quality of welds and ensures that there are no hidden defects that can lead to leaks or accidents. Ultrasound can detect internal defects in the material that are not always visible during visual inspection, and radiography can check the thickness and quality of joints at the molecular level. This control can remarkably improve the safety of pipelines. Another important aspect is flanged connections, which are used to connect pipes in places where it is necessary to provide convenient access for maintenance or repair. Multi-layer seals made of fluoroplast and reinforced graphite, which provide resistance to high temperatures, pressures, and protect against aggressive chemical influences, are used to increase the tightness of such connections.

One of the key elements for ensuring the safety of gas pipelines is segmentation and redundancy of the pipeline system. In the event of an accident, it is critical to quickly localise the damaged area and minimise the consequences for the entire network. Pipeline projects provide for the formation of technological zones using remote-controlled isolation valves. These valves allow effectively blocking certain sections of pipelines, which provides for a quick response to accidents without stopping the entire system. Isolation valves are usually installed in key areas where there is a chance of leaks or other malfunctions. It is also necessary to provide bypass circuits (bypass lines) in critical areas that ensure the continuity of gas supply during maintenance or in the event of an emergency. Bypass lines help avoid interruptions in gas supply and ensure its transportation via alternative routes, which greatly reduces risks and increases the overall reliability of the system. These design and engineering solutions provide the basis for safe, efficient, and reliable operation of gas supply systems, helping to minimise risks and ensure a stable supply of energy resources to consumers (Song *et al.*, 2021). In modern gas transmission networks, control and monitoring systems are a critical element of safe and efficient operation. These systems provide continuous monitoring of the technical condition of pipelines, rapid detection of deviations and maintaining the stability of technological processes. Comprehensive automation provides for moving from reactive to proactive risk management (Table 2).

Table 2. Types of sensors for detecting gas leaks

Sensor type	What it records	Accuracy	Reaction time	Features
CH_4 gas analyser	Methane concentration	±2 ppm	⩽5 s	High sensitivity, recommended for PE
Acoustic sensor	Leakage ultrasound	High	⩽1 s	It works even without direct contact
Pressure gauge module	Sudden pressure drops	0.05 MPA	instant	Easy installation, cheap
IR optical sensor	Spectral analysis of hydrocarbons	±1 ppm	⩽3 s	Contactless, high-precision

Source: compiled by the authors based on A. Swain *et al.* (2022)

The sensors considered for detecting gas leaks have different characteristics and applications. The CH_4 gas analyser detects methane concentrations with high sensitivity and accuracy up to ±2 ppm, with a reaction time of up to 5 seconds, making it effective for polyethene pipelines. The acoustic sensor, which detects leaks with ultrasound, has high accuracy and a response rate of up to 1 second, working without direct contact with the surface, which gives it an advantage in remote monitoring. The pressure gauge module detects sudden pressure drops with an accuracy of 0.05 MPA and responds instantly to changes, which ensures easy installation and low cost. The IR optical sensor performs spectral analysis of hydrocarbons, has a high accuracy of up to ±1 ppm and responds in 3 seconds, while not requiring contact with the object, which ensures high accuracy and safety during operation.

A key component of the digital transformation of the gas transportation infrastructure is the introduction of SCADA platforms. These complexes provide centralised management and monitoring of the entire gas supply system in real time. SCADA integration allows controlling electric gate valve drives, pressure regulators, gas analysers, temperature sensors, and emergency shut-off valves without the physical presence of the operator on site. In addition to management, SCADA systems implement telemetry with a high frequency of data collection, which allows dispatchers to quickly respond to changes in the functioning of the network. Due to the modular architecture, such complexes can be easily scaled and integrated with other digital platforms, in particular, analytical modules based on artificial intelligence (Eso & Eseosa, 2022).

One of the most dangerous incidents in gas transmission networks is a gas leak, so modern infrastructure should be equipped with high-precision leak detection systems. The most effective approach is the introduction of multimodal sensor networks, which include gas analysers that measure the concentration of methane (CH_4), propane, butane, and other hydrocarbons, acoustic sensors that detect sound signals characteristic of pipeline depressurisation, as well as pressure sensors that can detect abnormal fluctuations and drops that indicate losses. The Mass Flow Balance method is used to improve the accuracy of localisation, which is based on a mathematical analysis of the difference between the supplied and received gas volumes. This approach allows identifying not only the fact of the leak but also its approximate location with an accuracy of several tens of meters (Menon *et al.*, 2025).

A separate role in the monitoring structure is played by optical and thermal imaging systems that allow monitoring both the technical condition of equipment and the safety of objects from external interference. Video surveillance is implemented on the basis of intelligent analytical systems that can recognise non-standard behaviour of personnel, unauthorised entry, and other factors that can lead to a violation of the security regime. Such systems use computer vision algorithms that automatically identify events and generate alarm signals when threats are detected. High-resolution thermal imagers are used to detect equipment overheating, leaks, hot zones, or local insulation defects. This is especially important in high-load environments, where timely detection of overheating avoids failure of critical components (He *et al.*, 2024).

Thus, modern control and monitoring systems provide an opportunity to exercise full-scale control over all parameters of the pipeline network, ensuring its stable, safe, and predictable operation. Combined with analytical platforms and artificial intelligence, they become the basis for creating intelligent infrastructures capable of self-diagnosis and adaptive management. A reliable emergency protection system is a critical component of any gas transportation infrastructure. In conditions of increased man-made risks and difficult operating conditions, only timely detection of deviations and their automated localisation can guarantee the preservation of the integrity of the system, the life and health of personnel and the environment.

Emergency Shut Down (ESD) systems provide instant emergency response to prevent an event from escalating. They operate on the principle of automatic cut–off of gas supply when exceeding the specified parameters: temperature – to prevent thermal degradation of materials;

pressure – to avoid pipeline breaks; gas concentration in the air – to prevent the formation of explosive mixtures. It is based on electric shut-off valves with integrated controllers. In the event of a complete power outage, manual duplication is triggered – this allows technical personnel to manually cut off the supply, minimising the consequences even if automatic systems fail (Yusifov *et al.*, 2024).

In areas where explosive gases may accumulate, degassing systems are being introduced that operate on the principle of active ventilation and utilisation of excess gas. Ventilation units with adjustable air exchange ensure efficient dispersion of methane or other hydrocarbon accumulations, especially in technical rooms, wells, and chambers. In the event of a sudden release, the gas is sent to the gas collectors, where it accumulates and is then transferred to the flare installations. The latter implement controlled gas combustion, which allows avoiding explosions in case of uncontrolled leaks. These technologies minimise the risk of ignition and also comply with environmental standards for reducing emissions of hazardous substances into the atmosphere (Song *et al.*, 2021).

Active and passive fire protection systems are used to limit the spread of fire within the infrastructure. Active means are flame extinguishers – special devices that extinguish the reverse flame, preventing its penetration through the pipeline, and non-return valves with thermal protection, which are triggered when critical temperatures are reached, automatically blocking the gas transmission channel. Passive protection is implemented through the use of fire-resistant materials, in particular, compounds based on silicone, graphite, or cement matrices, for thermal insulation and thermal protection of pipes, and the application of fire-resistant paints and varnishes that foam when heated, creating a heat-insulating barrier. These measures can significantly improve the heat resistance of equipment and extend the time for personnel evacuation or emergency services (Donohue *et al.*, 2021).

Thus, a comprehensive emergency security system is not only a set of individual devices, but also an integrated preventive protection architecture that can diagnose a threat in a timely manner, neutralise its source, and localise its consequences. Its effectiveness largely depends on the technical level of implementation, routine maintenance, and continuous improvement in accordance with current risks. The functioning of gas transmission infrastructure facilities is impossible without a well-organised system of technical regulation, training of personnel, and ensuring compliance with international standards. It is organisational and technical security that creates a structured basis on which all processes of operation, maintenance, and emergency response are based.

Proper maintenance begins with system maintenance work performed following current regulations and license conditions. Scheduled licensing works include technical inspection of pipeline components, shut-off valves, pressure regulators, and other critical elements. The frequency and scope of work are determined individually for each object based on risk analysis and the age of the system. One of the most effective tools of modern diagnostics is in-tube inspection using intelligent pistons (smart pigs). These devices, equipped with a magnetic, ultrasonic, or electromagnetic sensor system, allow detecting internal defects in pipes (corrosion foci, reduced wall thickness, mechanical displacements, cracks) without stopping the gas supply. These measures increase the level of security and extend the life cycle of infrastructure facilities (Amaechi *et al.*, 2022).

The human factor remains one of the main sources of risk in any production processes, so a high level of personnel training is a critical condition for safe operation. Emergency response training includes modelling critical situations (gas leak, fire, explosion) using realistic scenarios. Such training allows developing the skills of staff to quickly assess the situation and make decisions. Additionally, training is provided on working with modern monitoring and automation tools – from SCADA systems to local sensor modules. Employees should be able to quickly interpret signals, diagnose malfunctions, and initiate emergency response (Chen *et al.*, 2021).

Documenting all technical and organisational processes ensures transparency, accountability, and compliance with government and international regulatory requirements. The key standards that ensure the safety and efficiency of work in gas transmission networks are international and European standards that regulate various aspects of safety, labour protection, and environmental management. ISO 45001:2018 (2018) is an international occupational health and safety management system that is the basis for creating a safe working environment. This standard defines the requirements for the development and implementation of an occupational safety management system in organisations, ensuring effective control over possible risks to the health and safety of personnel. According to ISO 45001:2018 (2018), organisations must implement safety policies, risk assessment, accident prevention measures, and the creation of safe working conditions. The standard provides for the active involvement of management in the implementation of security policies, monitoring, and measuring the results of the system, in addition to the regular improvement of security practices in accordance with changing production conditions.

ISO 14001:2015 (2015) is an international standard for environmental management that sets out requirements for the creation, implementation, and improvement of an environmental management system (EMS). ISO 14001:2015 (2015) requires organisations to constantly monitor emissions of harmful substances into the atmosphere, water, and land resources, along with the leaks of toxic gases or other hazardous materials. This allows not only to minimise the negative impact on the environment but also to ensure compliance with environmental requirements defined by international agreements and national legislation. The implementation of ISO 14001:2015 (2015) requires monitoring environmental indicators, conducting environmental impact assessments, and identifying preventive measures to prevent environmental disasters.

EN 15001-1:2023 (2023) is a European standard that defines technical requirements for the design, installation, and operation of gas distribution systems. It covers both the construction of new gas installations and the modernisation of existing ones. EN 15001-1:2023 (2023) provides requirements for the quality of materials used in the construction of gas pipelines, safety during their installation, and for pipeline monitoring and maintenance systems during operation. The standard aims to improve the safety of gas installations, reduce the likelihood of accidents such as gas leaks or explosions, and ensure proper energy and resource efficiency in gas systems. EN 15001-1:2023 (2023) also contains recommendations for regular inspections and diagnostics of gas networks to detect possible defects or malfunctions in their operation in a timely manner. These standards provide an integrated management system for safety, occupational health, environmental responsibility, and quality in the gas industry, which is essential to reducing risks and improving operational efficiency in this area. All processes must be accompanied by technical documentation, which includes: passports and diagrams of objects, maintenance logs, inspection and repair reports, protocols for training personnel and responding to accidents.

Together, these organisational and technical measures form a single safety management system that both minimises the risks of accidents and guarantees compliance with the highest industry requirements. Their implementation requires continuous improvement, a systematic approach, and integration with modern technology platforms. In modern operating conditions of complex engineering facilities, such as gas transmission systems, innovation becomes not just a factor of modernisation, but a necessary condition for ensuring reliability, safety, and efficiency. Infrastructure intellectualisation allows moving from reactive to proactive risk management (Table 3).

Table 3. Unmanned pipeline inspection platforms

UAV type	Sensors on board	Range (km)	Purpose	Advantages
DJI Matrice multicopter	4K camera, FLIR thermal imager	5	Local node diagnostics	High accuracy, vertical take-off/landing
EBee X cruise drone	LIDAR, GPS, RGB camera	50	Aerial photography of main sections	High autonomy, covering large areas
Hybrid WingtraOne	Gas analyser CH_4 + thermal scanner	15	Probing hard-to-reach areas	Combines range and flight stability

Note: UAV – an unmanned aerial vehicle
Source: compiled by the authors based on Y.M.R. Da Silva *et al.* (2022)

Three types of UAVs for pipeline inspection are presented, each of which has its own characteristics and purpose. The DJI Matrice multicopter is equipped with a 4K camera and a FLIR thermal imager, which allows local diagnostics of pipeline components at a distance of up to 5 km. The main advantage is high accuracy and the possibility of vertical take-off and landing, which is convenient for examining complex objects. The eBee X cruise drone with LIDAR sensors, GPS, and an RGB camera is designed for aerial photography of main sections of pipelines, covering large areas with a range of up to 50 km. Its advantage is high autonomy and the ability to work over long distances. The hybrid WingtraOne, equipped with a CH_4 and gas analyser and a thermal scanner, allows probing hard-to-reach areas at a distance of up to 15 km. The advantage of this drone is the combination of flight range and stability, which is important for accurate measurements in difficult conditions. In general, each UAV has its own specifications for different tasks, which provides flexibility in applications for monitoring and inspecting pipelines.

The use of IoT devices provides for continuous monitoring of critical parameters of the pipeline infrastructure-pressure, temperature, vibrations, humidity, and the composition of the gas mixture. Data from thousands of nodes is read in real time, transmitted to analytical platforms, and enables quick detection of even minor deviations from nominal values. Due to this, it is possible to quickly identify potential problems and take timely measures to eliminate them, which increases the safety of operation and lowers the risk of accidents. Of particular importance is the concept of digital twin – a virtual model of a real object, which is updated based on factual data from field sensors. Engineers can conduct virtual tests of equipment degradation scenarios, simulate the consequences of accidents or emergencies, and optimise maintenance schedules using this model. The digital twin predicts the behaviour of the pipeline system, which allows planning for more efficient use of resources and reduces the possibility of equipment failures, identifying potentially dangerous areas in a timely manner. This substantially improves risk management and ensures the continuity of the gas transmission network (Singh *et al.*, 2021). AI is increasingly being implemented in the service sector of pipeline systems. Its main function is to analyse large amounts of data to identify hidden patterns and trends that may indicate the approach of a potential failure or critical state of a system element. The use of AI can immensely improve pipeline monitoring and management processes, making them more efficient and secure.

In particular, machine learning algorithms are used to classify behavioural anomalies in the operation of equipment, which allows identifying non-obvious changes in the operation of the system that may precede serious problems. Neural network forecasting models based on historical data from previous incidents are also actively used, helping to anticipate possible failures and take the necessary measures in a timely manner. In addition, automatic decision-making systems are being developed that generate recommendations to dispatchers in real time, contributing to a quick response to potential emergencies. Thus, AI becomes a key element of the transition to predictive maintenance, which vastly reduces the risk of accidents, allowing maintenance and repairs to be conducted based on real data, rather than on schedule, which in turn helps to optimise costs and improve the efficiency of the pipeline system (Sircar *et al.*, 2021).

Monitoring the state of gas transportation infrastructure, especially in hard-to-reach areas (mountainous terrain, forest areas, swampy areas), is greatly simplified by using UAVs. Modern drones are equipped with high-precision cameras, thermal imagers, LiDAR, and gas analysers, which enables aerial photography of linear objects with precise positioning, detection of temperature anomalies associated with gas leaks or thermal degradation of materials, scanning of terrain and vegetation to assess external risks (soil erosion, damage to root systems, etc.). Automated drone patrolling not only increases the speed of the survey but also reduces costs and risks for personnel (Askarzadeh *et al.*, 2024). Innovative solutions are not the future, but an integral part of the present gas transportation industry. Their implementation allows identifying potential threats even before they materialise and creating an adaptive, self-learning infrastructure that can quickly respond to the challenges of the man-made environment. The development of such technologies defines a new paradigm – an intelligent infrastructure with zero fault tolerance.

Discussion

In the course of the study, structural and engineering solutions aimed at improving the reliability and durability of pipeline systems were analysed. Special attention was paid to the quality of materials – the use of anticorrosive alloys, in particular, stainless steels and composites, substantially reduced the risk of premature wear of pipes. The high resistance to pressure and temperature also confirmed the effectiveness of the selected materials, and polymer pipes showed the feasibility of using them in internal networks, provided that the standards are met. This problem was also investigated by A. Reda *et al.* (2025), where the results confirmed that corrosion is one of the main causes of premature pipeline wear, especially in aggressive environments. The use of corrosion-resistant alloys, such as stainless steel or titanium, considerably extends the service life of the equipment. A good choice of material reduces repair and maintenance costs, increasing the overall reliability of the system. A.C.C. De Leon *et al.* (2021) also indicated that polymer and metal composites exhibit high strength and chemical resistance, making them promising for pipeline systems. Their use decreases the weight of structures and improves corrosion protection without losing mechanical properties. Modern composite manufacturing technologies also contribute to improving the energy efficiency and durability of the gas transportation infrastructure.

Notably, the choice of materials should consider corrosion resistance, along with the economic feasibility and operating conditions of the pipeline. For example, in regions with high humidity or in environments with aggressive impurities, it is more appropriate to use more expensive but durable materials. In addition, the technological compatibility of materials with existing systems and the possibility of their maintenance throughout the entire life cycle play a major role. It was determined that the reliability of joints increased remarkably when using automated welding systems supplemented with non-destructive testing. Quality control of welds using ultrasound or radiography has reduced the likelihood of defects leading to leaks. Furthermore, flanged connections with highly reliable seals demonstrated high tightness under high-pressure conditions. J.L. Velázquez de la Hoz & K. Cheng (2021) concluded that automated welding systems provide high accuracy and repeatability of the process, which is especially important in the construction of long-haul pipelines. The use of non-destructive testing – ultrasonic, X-ray, or magnetic – allows detecting defects even at the installation stage. This approach increases the reliability of the system and reduces the risk of accidents during operation. B. Li *et al.* (2024) established that flanged connections designed for high pressure provide tightness even in difficult operating conditions. They are easily dismantled and help to quickly maintain or replace individual pipeline components. Due to the use of modern sealing materials, the probability of leaks is noticeably reduced, which is critical for the safety of gas transportation infrastructure. These results confirm the above study, as they demonstrate a close relationship between the quality of welding seams and the overall reliability of the gas transmission system. Automation of processes and the introduction of non-destructive testing allow minimising the human factor, which is a fundamental factor in ensuring the stable operation of pipelines. Consequently, improving quality standards at the construction stage directly affects the safety and durability of the entire infrastructure.

The results of zoning pipeline networks showed that the division into isolated sections with remote control and the presence of bypass lines greatly increased the flexibility and safety of the system. In the event of an accident, it became possible to quickly localise the problem area without stopping the entire complex. The paper of S. Zhang *et al.* (2023) is notable, having determined that the integration of remote-controlled gate valves into the pipeline assists in timely isolating the emergency section without having to stop the entire system. This minimises the response time and potential gas losses. This segmentation enhances operational safety and simplifies maintenance of large gas transmission networks. In turn, J. Chen *et al.* (2022) concluded that bypass lines allow redirecting the flow of gas to bypass the damaged or serviced area, while maintaining a constant supply to consumers. They are particularly effective in case of accidents or during scheduled repairs, when it is crucial to avoid interruptions in the supply. Thus, such lines help to increase the reliability and flexibility of the entire gas transmission system. These data correspond to the theses given in this study, confirming the effectiveness of using remote-controlled gate valves and bypass lines in ensuring stable operation of the system. Due to such technical solutions, the gas transmission infrastructure becomes more adaptive to emergency situations and less vulnerable to interruptions. This, in turn, strengthens the overall security and energy independence of regions that depend on a continuous gas supply.

Control and monitoring systems were also analysed, among which SCADA complexes demonstrated their effectiveness in collecting and processing telemetric data. Leak detection systems that use methane, pressure, and noise sensors accurately detect even minimal deviations from normal conditions, and mass balancing methods help localise leaks with high accuracy. E.B. Priyanka *et al*. (2021) also conducted a study, the results of which confirmed that the introduction of SCADA systems with telemetry allows monitoring and controlling the operation of gas pipelines in real time. Intelligent analysis of data from such systems helps to anticipate possible emergencies and take timely measures to prevent them. This substantially increases the efficiency of infrastructure management and minimises the human factor in the control and configuration process. J. Bin *et al*. (2022) also proved that sensor technologies, along with thermal imaging diagnostics, provide fast and accurate detection of gas leaks, which is critical for pipeline safety. Thermal imagers allow detecting even the slightest temperature changes that may indicate a gas leak, while sensors constantly monitor the composition of the air. These innovative methods enable a swift localisation of the problem, minimising the risks and costs of repairs. Comparing the data obtained in the course of the current study, it can be concluded that the integration of SCADA systems and sensor technologies greatly increases the level of safety and efficiency of the gas transmission infrastructure. The use of these technologies provides for not only quickly identifying emergency situations but also predicting possible problems, which reduces the time to fix them. This integrated application of intelligent systems and sensors creates prerequisites for more stable and safe operation of pipelines.

In the field of safety, emergency shutdowns and degassing systems were effective, which made it possible to quickly stop the gas supply and remove surpluses from hazardous areas. The incorporation of fire protection measures, specifically thermal fuses and fire-resistant materials, enhanced the overall fire resistance of the object. K. Cameron *et al*. (2023) concluded that ESD emergency modules can instantly stop gas supply in the event of an emergency, thereby preventing further spread of the danger. The electric drive fittings integrated with these modules ensure fast and accurate execution of necessary operations in remote areas without human intervention. This lowers the response time to accidents and increases the reliability of the gas transmission system. K. El-Borhamy *et al*. (2022) stated that degassing and ventilation systems provide efficient removal of hazardous gases from pipelines and prevent the accumulation of explosive mixtures in confined spaces. Fire-resistant systems, in turn, minimise the risk of fire and provide additional protection in high-temperature conditions. The integrated use of these systems in critical areas can increase the level of safety and ensure the continuity of the gas transmission infrastructure.

When analysing the results of the study, it is clear that the integrated use of emergency ESD modules, electric drive fittings, in addition to degassing, ventilation, and fire protection systems, can remarkably reduce the risks of accidents and ensure the reliability of the gas transmission infrastructure. The use of automated systems for emergency response both improves safety and optimises management processes under high loads. These technologies are an important step towards creating more stable and resistant gas pipelines to external and internal threats. Finally, organisational and technical measures played an equally important role. Routine inspections and in-tube diagnostics helped detect damage at an early stage, and staff training ensured an effective response in emergency situations. In general, the study confirmed that the safety of gas pipeline systems is possible only with a comprehensive approach that covers materials, technologies, monitoring, operation, and innovation.

Conclusions

As a result of the study, it was determined that modern gas transmission systems require a comprehensive approach to design, monitoring, and operation. The basis of a reliable infrastructure is the use of high-quality pipe materials that can withstand aggressive environments and high loads. For example, austenitic stainless steel has a high resistance to corrosion, operates at pressures up to 2.5 MPA and temperatures up to +120 °C, which makes it optimal for main gas pipelines. PE100 polyethene is widely used in distribution networks, designed for pressures up to 1.0 MPA and temperatures up to +40 °C. Leak detection has become more accurate due to modern sensors. Methane gas analysers respond with an accuracy of ±2 ppm in ⩽5 seconds, and contactless IR optical sensors and acoustic modules ensure fast response even without physical access to pipes. The combination of these technologies with thermal imagers and SCADA systems for real-time monitoring is particularly effective. Drones are used for inspections of hard-to-reach areas. For example, the DJI Matrice multicopter (radius up to 5 km) is equipped with a 4K camera and a FLIR thermal imager, while the winged eBee X (up to 50 km) has LIDAR and an RGB camera. The hybrid WingtraOne combines a CH_4 gas analyser and a thermal scanner, which allows sensing even in difficult terrain.

Overall safety is maintained through emergency systems, degassing installations, fire protection, and compliance with international standards ISO 14001:2015, ISO 45001:2018, and EN 15001-1:2023. Development prospects are connected with digital doubles, IoT, and AI analytics, which form a new quality of operation. A limitation of the study was that the analysis was conducted on the basis of theoretical models and general technical solutions without accounting for the specifics of specific operating conditions in individual regions. Further research should focus on the effectiveness of using artificial intelligence in long-term forecasting of pipeline system wear in various climatic zones.

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Аналіз технічних рішень для забезпечення безпеки трубопровідного транспорту газу на великих промислових об'єктах

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Анотація. Метою цього дослідження було забезпечення підвищення надійності та безпеки експлуатації газових трубопроводів шляхом детального аналізу сучасних технічних рішень, інноваційних технологій та ефективних методів контролю. Проаналізовано сучасні технічні та організаційні рішення для забезпечення безпеки трубопровідного транспорту газу на промислових об'єктах. Встановлено, що найвищу ефективність демонструє поєднання автоматизованих систем контролю, застосування корозійностійких матеріалів і сегментації мереж за допомогою аварійних засувок. Проаналізовано технічні характеристики основних матеріалів труб: зокрема, аустенітна нержавіюча сталь витримує до 2,5 мегапаскалів при температурі +120°C, що робить її придатною для магістральних газопроводів; поліетилен (PE100) забезпечує експлуатацію при тиску до 1,0 мегапаскаля і температурі +40°C, що підходить для підземного газопостачання. Також розглянуто типи сенсорів, зокрема газоаналізатори метану з точністю ±2 частинки на мільйон і часом реакції до 5 секунд, що особливо ефективно для полімерних труб. Узагальнено досвід використання інтелектуальних приладів для внутрішньотрубної діагностики, здатних виявляти механічні дефекти без зупинки транспортування. Окрему увагу приділено застосуванню безпілотних літальних апаратів: мультикоптери з тепловізорами і крилаті дрони з лазерним сканером дозволяють оперативно обстежувати важкодоступні ділянки протяжністю до 50 км. Зроблено висновок про необхідність інтеграції цих рішень у комплексну систему технічного обслуговування. Отримані результати можуть бути використані для розробки та впровадження сучасних комплексних систем безпеки на промислових об'єктах, що сприятиме зменшенню аварійності та підвищенню надійності газотранспортної інфраструктури

Ключові слова: моніторинг; діагностика; витік; корозія; автоматизація; інновації

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