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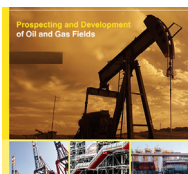
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Features of operation of a watered gas well with a plunger lift

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Abstract. To obtain high values of the current gas production and the final coefficient of gas extraction from deposits under the water-pressure regime, it is necessary to ensure complete and continuous removal of liquid from the bottom hole to the surface. An effective method of intensifying the operation of watered gas wells and extending the period of their natural flow is the use of a plunger lift. The purpose of the study was to substantiate the area of effective use of a plunger lift to intensify the removal of fluid from watered gas wells using the reservoir gas's own energy depending on the value of the water factor. The tasks were solved by conducting research on a hypothetical (model) watered gas well using mathematical modelling methods. The proposed mathematical model of the plunger lift operation has been tested for the conditions of a hypothetical gas well at different values of the water factor from 0 to 125 L/thousand m³. For the well under consideration, the area of effective application of the plunger lift is limited to the values of the water factor of 12-41 L/thousand m³. According to the research results, the maximum value of the width of the gap between the plunger body and the wall of the tubing, which should not exceed 0.0025 m, is substantiated. The developed mathematical model of the plunger lift operation in a watered gas well, which includes the choice of the area of its effective application and the maximum value of the gap width between the plunger body and the tubing wall, makes it possible to ensure stable operation of watered gas wells with increased gas production due to the use of reservoir gas's own energy and to extend the wells' flowing period. As a result, in practice, the current gas production and the final coefficient of gas extraction from the field are increased

Keywords: productivity; water factor; mechanised operation; minimum required gas flow rate; effective application area; gap width

Introduction

When gas fields are operated under water pressure, there is an increase in well water cut, which negatively affects gas production. As the water factor increases and reservoir energy decreases, fields use a variety of methods to remove

water from the well and maintain productivity, including physical, chemical and mechanical methods. The use of a plunger lift is highly efficient because of its simple design and maintenance. The use of a plunger lift increases the

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time of active gushing of wells, which are characterised by a significant amount of liquid in the extracted products, and in the case of periodic gas lifts, it helps to reduce the need for additional gas to lift the liquid from the bottom hole to the surface. Therefore, further research into the operation of a watered gas well with a plunger lift deserves attention.

As noted by such scientists as J.J. Marques De Jesus & G. Simonelli (2018) and S. Rajvanshi *et al.* (2023), in gas wells, tubing of a smaller diameter is installed to maintain the inflow of reservoir fluids, or a gas lift method of operation is used. However, neither reducing the diameter of the tubing nor using a gas lift is a permanent solution to the problem of operating watered wells, as the gas velocity first increases to carry the fluid out of the bottom hole, and then at some point the gas velocity decreases again to an insufficient level, and the fluid will not be carried out of the well.

The plunger lift is one of the most common and effective methods of removing fluid from the well under certain conditions, which is also described by T. Nguyen (2020) and Z. Nurkas (2020). The experience of operating plunger lifts and their availability is a big challenge for the Ukrainian industry. In Pakistan, pilot projects are being effectively implemented to help build experience and competence in the general application of plunger lifts in the industry. They are used in wells with a high water factor value, in wells without a packer, and in wells with a packer. Since packer wells cannot use annular gas as a source of energy, the plunger lift depends solely on the energy of the formation gas coming from the bottom of the plunger. Packer wells require special approaches for effective production management.

The use of a plunger lift for watered gas wells is an intermediate option between the traditional fountain method and the gas lift (pump) method of operation, as described by M. Burns (2018). The use of a plunger lift in combination with a gas lift allows for increased production, reduced operating costs and more efficient use of reservoir energy in fields. The combination of gas-lift and plunger technologies provides oil and gas operators with opportunities to optimise production from the initial stage of development, which is characterised by high initial fluid flow rates, to the completion of fields for depletion, according to B. Cope & D. Gilmore (2023).

A typical plunger lift model consists of tubing with shock absorbers at both ends and a plunger between them. The plunger is available in two versions: with a gap between its body and the inner surface of the tubing or with a sealing plug. During well operation, the plunger cycles through the tubing string, moving up and down, lifting fluid from the well with each upward movement. Many types of plungers have been proposed, which differ in the design of the plunger body and valve assembly; in particular, the study by Z. Nurkas & K. Khabibuyev (2020), which examined the latest innovations in Kazakhstan.

The scope of effective use of plunger lifts for water removal from watered gas wells is limited by the water factor (water flow rate). At low water factors, when water is carried out of the bottom hole by the formation gas flow, there is no need to equip the well with a plunger lift. With high

water factors, the reservoir gas energy is insufficient for both well flow and plunger lift operation. There is no data in the technical literature on the selection of the area of effective use of the plunger lift for the operation of watered gas wells depending on the water factor, which served as the basis for additional research. The purpose of the study was to substantiate the methodology for selecting the scope of effective use of a plunger lift for the operation of watered gas wells depending on the value of the water factor.

Materials and Methods

A study to substantiate the method of choosing the scope of effective use of a plunger lift for the operation of watered gas wells, depending on the value of the water factor, was performed for the conditions of a hypothetical (model) gas well for the following data: the depth of the production well (the depth of lowering of tubing pipes) is 2,300 m; the inner diameter of the production column is 0.146 m; the inner diameter of the tubing is 0.062 m; reservoir pressure is 6.2 MPa; well pressure is 4.4 MPa; the relative density of the gas is 0.6; reservoir water density is 1,028 kg/m³; coefficients of filtration resistances of the bottom-hole zone of the formation: $A = 0.25$ (MPa² × day/thousand m³); $B = 19 \times 10^{-4}$ (MPa × day/thousand m³)²; the width of the gap between the plunger body and the tubing is 0.002 m. The parameters of well operation when only gas enters the face, determined from the joint solution of the binomial formula for gas inflow to the bottom of the well and the formula for gas flow to the tubing using the work dependencies for constant well pressure (4.4 MPa), are: gas flow rate – 30.1 thousand m³/day, downhole pressure – 5.4 MPa. In the studies, gas enters the well from a gas-bearing formation, and water enters from a watered formation. The study was performed at a constant value of the wellhead pressure (4.4 MPa) and under conditions of changes in the water factor indicators (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 125 L/thousand m³).

To determine the lower limit of the water factor, from which it is economically feasible to use a plunger lift in watered gas wells, the gas flow rate from the formation was calculated for different values of the water factor, and the minimum required gas flow rate was established to ensure the removal of fluid from the bottom hole. The calculation of reservoir gas flow rate was carried out on the basis of solving a combined problem, which includes a binomial formula for gas inflow to the well and a formula that takes into account additional pressure losses in the tubing when moving a two-phase flow according to a certain method (Lea & Nickens, 2004; Matkivskiy & Khaidarova, 2021). The minimum required gas flow rate is determined by the formula given (Kondrat & Matiishyn, 2022). This relationship was derived from statistical analysis of data obtained during the operation of watered wells in a particular field:

$$q_{mr} = 2,213 \times d_{in}^{1.94} \times q_l^{0.22} \times \sqrt{\frac{P_{ah} \times \rho_l}{\bar{p}_g \times Z_{ah} \times T_{ah}}}, \quad (1)$$

where q_{mr} – minimum required gas flow rate, thousand m³/day; q_l – the flow rate of liquid (water), which was

determined as the product of the water factor and the flow rate of reservoir gas for this factor, m^3/day ; P_{dh} – downhole pressure, MPa; T_{dh} – downhole temperature, K; d_{in} – inner diameter of tubing, m; ρ_l – liquid density by P_{dh} and T_{dh} , kg/m^3 ; $\bar{\rho}_g$ – relative gas density; Z_{dh} – gas compressibility coefficient by P_{dh} and T_{dh} . To lift the plunger, a certain amount of gas is required, which includes the volume of gas to create the required pressure in the tubing below the plunger, as well as the volume of gas passing through the gap between the plunger and the inner surface of the tubing:

$$V_g = 10^{-5} \times L \times f_{pl} \times P_g + q_{los} \frac{L}{W_{pl}}, \quad (2)$$

where V_g – volume amount of gas for lifting the plunger, m^3 ; L – tubing length from the mouth to the lower shock absorber, m; f_{pl} – cross-sectional area of the plunger lift, m^2 ; P_g – gas pressure under the plunger, which is necessary to lift the plunger with a column of liquid above it, Pa; q_{los} – gas losses from under the plunger through the gap between the plunger and the tubing wall, m^3/s ; W_{pl} – plunger lifting speed, m/s. The rate of rise of the plunger is determined by the formula:

$$W_{pl} = 50 \times \sqrt[3]{\frac{S \sqrt{10^3}}{h_l \times \rho_l}}, \quad (3)$$

where h_l – height of the liquid column above the lower shock absorber, m; ρ_l – liquid density, kg/m^3 ; S – width of the gap between the plunger and the tubing wall, m. The height of the liquid column above the lower shock absorber is determined by the formula:

$$h_l = \frac{P_a}{\rho_l \times g}, \quad (4)$$

where P_a – pressure of the gas-liquid mixture in the tubing at the level of the lower shock absorber, Pa. The pressure of the gas-liquid mixture in the tubing at the level of the lower shock absorber is determined by the formula:

$$P_a = P_{dh} - h_e \rho_l g, \quad (5)$$

where h_e the distance from the elevator shoe to the lower shock absorber (taken equal to 25-50 m). It was taken that $h_e = 25$ m in the calculations. Gas loss from under the plunger through the gap between the plunger and the tubing wall is determined by the formula:

$$q_{los} = 271.96 \times d_{in} \times S \times \sqrt{P_g}. \quad (6)$$

The gas pressure under the plunger, which is required to lift the plunger with a column of liquid above it, is calculated using the formula:

$$P_g = h_l \rho_l g + \lambda \frac{h_l W_{pl} \rho_l}{2 d_{in}} + P_{wh} + P_{fr} + P_w, \quad (7)$$

where λ – coefficient of hydraulic resistance (0.025 was taken in the calculations); P_{wh} – pressure at the wellhead, Pa; P_{fr} – pressure expended to overcome the friction of the plunger, Pa; P_w – pressure expended to overcome the weight of the plunger, Pa. The pressure expended to overcome the friction of the plunger was calculated to be equal to $P_{fr} = 10^4$ Pa; the

pressure expended to overcome the weight of the plunger – $P_w = 2 \times 10^4$ Pa. The amount of gas flowing from the formation during the plunger lift (V_{gp}) is determined by the formula:

$$V_{gp} = q_g(t) \times t, \quad (8)$$

where q_g – gas production rate, m^3/s ; t – plunger lifting time, s. The lifting rise time is determined by the formula:

$$t = \frac{H - h_e}{W_{pl}}, \quad (9)$$

where H – well depth, m. The amount of gas entering the tubing (V_{glos}) is calculated using the formula:

$$V_{glos} = V_{gp} \frac{f_{pc}}{F}, \quad (10)$$

where f_{pc} – cross-sectional area of the production column, m^2 .

Results and Discussion

Studies on the operation of a watered gas well with a plunger lift have shown its high efficiency. The research results are shown in Figure 1 as dependences (obtained by formula (1) of the reservoir gas flow rate q_r (curve 1) and the minimum required gas flow rate q_{mr} (curve 2) from the water factor F_w . According to the research results, with an increase in the water factor, the flow rate of reservoir gas decreases (curve 1) from 30.1 thousand m^3/day in the absence of water in reservoir products up to 18.8 thousand m^3/day for water factor 125 L/thousand m^3 (water flow rate 2.35 m^3/day), and the minimum required gas flow rate increases (curve 2) and reaches a value of 47.2 thousand m^3/day for water factor 125 L/thousand m^3 . If the water factor does not exceed 12 L/thousand m^3 (which corresponds to a water flow rate of up to 0.31 m^3/day), the well operates efficiently, using the energy of the extracted gas to remove water. With higher water factors, additional measures must be taken to effectively remove water from the well. The value of the water factor of 12 L/thousand m^3 can be considered as the minimum indicator for using a plunger lift. It should also be noted that in Figure 1, the right part of the gas flow rate curve is “conditional”, because with water factors above 12 L/thousand m^3 , the well is usually not operated.

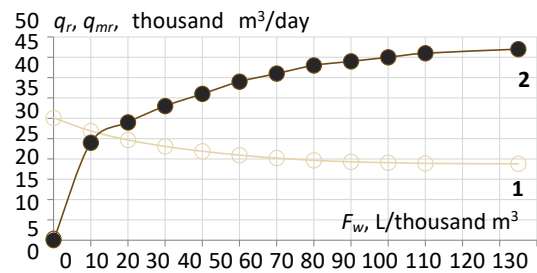


Figure 1. Reservoir gas flow rate dependencies q_r (1) and the minimum required gas flow rate q_{mr} (2) from the water factor F_w

Source: created by the authors

To determine the maximum possible use of a plunger lift in a particular well, it is necessary to calculate how much gas is required to lift the plunger, taking into account different water factor values (or water flow rates). The volume of gas that naturally escapes from the formation

during the time it takes to lift the plunger must also be taken into account. For a plunger lift unit to operate without surface gas, the amount of gas flowing from the formation into the tubing during the plunger lift must be greater than the amount of gas required to lift the plunger. Figure 2 shows the dependence of the required amount of gas for lifting the plunger V_g (curve 1) and the actual amount of gas coming out of the reservoir during the lifting of the plunger V_{gp} (curve 2) from the water factor F_{wv} .

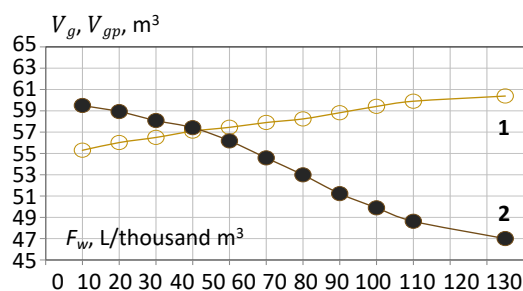


Figure 2. Dependences of the required amount of gas for lifting the plunger V_g (1) and the actual amount of gas coming from the reservoir V_{gp} (2) from the water factor F_{wv}

Source: created by the authors

According to the results of research, with an increase in the water factor, the required amount of gas for lifting the plunger increases from 55.3 m^3 (with a water factor of 10 L/thousand m^3) up to 60.4 m^3 (with a water factor of 125 L/thousand m^3) and the amount of gas coming from the reservoir decreases from 59.5 m^3 up to 47 m^3 . The plunger lift operates without gas supplied from the surface to the water factor value of 41 L/thousand m^3 (accounts receivable 0.9 m^3 /day). At higher water factors, the use of a plunger lift is not feasible, as less gas flows from the reservoir than is required to lift the plunger. Thus, for the conditions of the well under study, the range of effective use of the plunger lift is within the range of changes in the water factor of 12-41 L/thousand m^3 . For the water factor value of 41 L/thousand m^3 , the effect on the required amount of gas for lifting the plunger is studied V_g and the actual amount of gas coming from the reservoir V_{gp} , the width of the gap between the plunger body and the tubing wall, which varied in the range of 0.001-0.005 m. The relevant dependencies are shown in Figure 3.

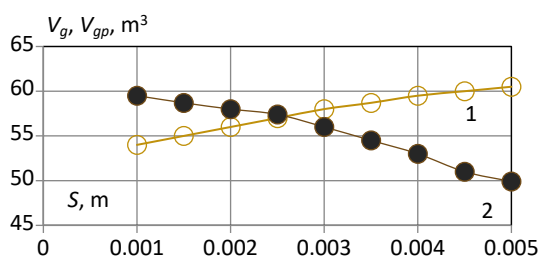


Figure 3. Dependences of the required amount of gas for lifting the plunger V_g (1) and the actual amount of gas coming from the reservoir V_{gp} (2) from the width of the gap between the plunger body and the tubing wall S

Source: created by the authors

The proposed methodology for selecting the scope of effective use of a plunger lift for water removal from watered gas wells depends on the current and forecast values of the water factor. The minimum value (lower limit) of the water factor, starting from which it is advisable to use a plunger lift, is determined by the parameters of the intersection point of the graphical dependencies of the reservoir gas flow rate and the minimum required gas flow rate for water removal from the well on the water factor. The maximum value (upper limit) of the water factor, above which the reservoir gas energy is insufficient for the plunger lift to operate, is determined by the parameters of the intersection point of the graphical dependencies of the required amount of gas to lift the plunger with the water column above it and the actual amount of gas coming from the reservoir during the plunger lift on the water factor. For the conditions of the considered hypothetical (model) well, the scope of effective use of the plunger lift is limited to the values of the water factor of 12-41 L/thousand m^3 . For a maximum water factor of 41 L/thousand m^3 , the width of the gap between the plunger body and the tubing wall should not exceed 0.0025 m. At larger gap widths, the amount of gas coming from the formation is less than the required amount of gas to lift the plunger, and the well will not operate.

The mechanised operation of gas and gas condensate wells is effective in water-flooded conditions. Using Schlumberger's PipeSim software, S. Matkivskiy et al. (2021) and S. Matkivskiy & L. Khaidarova (2021) performed the studies to optimise the operating conditions of a watered well under conditions of active reservoir water supply to gas-saturated productive horizons. Based on the results obtained, the optimal depth of gas-lift valves from the wellhead was determined, which is 55-58% of the depth of the tubing run. R. Kondrat et al. (2017) and R. Kondrat & L. Matiishyn (2022), based on the results of statistical analysis of the calculated data, determined the optimal values of gas lift gas flow rate for different values of the water factor, which ensure maximum well productivity and minimum values of bottomhole pressure.

In addition to gas lift operation, a plunger lift is also successfully used for liquid removal. The plunger lift method has long been successfully implemented at wells in Europe, including in neighbouring Romania. This technology is designed to solve the problem of waterflooding, a very common problem in wells. The cycle time of the plunger as it moves up and down the well depends on various factors such as well pressure, water volume, well depth, etc. There are different types of plungers with different prices, but they all work on the same principle: they rise up the pipe under the action of gas pressure, pushing the liquid out. The main characteristics of the plunger include the time required for one cycle and the speed of its upward movement (Rajvanshi et al., 2023). The frequency of cycles, as well as other factors, affect the service life of the plunger, which is typically designed to last between two and four months before the first inspection. After this period, the equipment should be serviced. The entire process can be monitored remotely using sensors, the data from which is transmitted to a computer via a wireless Internet connection.

The authors, after comparing the calculated results with the actual well loading data, identified systematic errors of empirical models, which prompted the development and implementation of a model that provides higher accuracy in predicting critical flow rates based on actual well flow rates (Rahmati *et al.*, 2022; Olszak *et al.*, 2022). The advantages of implementing plunger lift technology are the simplicity and speed of installation, efficiency and relatively low cost of the system. At the same time, there are limitations to the application of this technology, which are based on the fact that the well must produce a certain gas flow rate in order to push out the plunger and the accumulated fluid. There are also limitations to the implementation of plunger lift technology in terms of depth – they are used mainly in wells up to 3,000 m. The use of a plunger lift made it possible to resume production at the stopped well and reach indicators of 5 m³/day of oil production and 15 thousand m³/day gas supply. The installation of the plunger system has reduced capital expenditure by more than 3 times compared to traditional rod and submersible pump systems. The installation of a plunger lift is effective for a long period of well operation by maintaining reservoir energy. If reservoir energy is not sufficient during the operation of watered wells, additional gas injection into the annulus is necessary, according to G.M. Hashmi *et al.* (2016).

Any model – whether physical, empirical or AI-based – relies entirely on a high-frequency stream of high-quality data provided by the sensors to derive a conclusion about the current state of flow in the wellbore. External variables such as line pressure can change dramatically within minutes (e.g., due to compressor failure), which in turn can cause the well to fail to lift the plunger and fluid load to the surface, increasing the likelihood of a fluid influx. An automated setpoint optimisation solution that receives high-frequency data can detect such changes in time and take immediate corrective action to eliminate the potential consequences of such pressure spikes in the line. Therefore, scientists have developed algorithms that initially used modern critical flow equations, such as the equation by Z. Wang *et al.* (2017) for calculating critical flow rates. After comparing the calculated results with actual well loading data, they found large systematic errors in empirical models, prompting them to develop and implement a data-based model that provides higher accuracy in predicting critical flow rates based on actual flow rates (Rahmati *et al.*, 2022). Another example is the adaptation of setpoint optimisation algorithms to automatically determine the time of plunger fall. The drop time is usually set based on the general drop rates provided by the plunger manufacturers. These fall rates do not take into account the effects of the density and viscosity of the fluid in the tubing string and can therefore greatly overestimate or underestimate the actual fall time.

The continuous flow plunger lift is not limited to gas well delimitation and is also suitable for wells with higher flow rates. O. Sayman *et al.* (2022) presented wells with a flow rate of more than 500 thousand barrels of oil and 2 million cubic feet of gas per day with 2-7/8 inch outer diameter tubing and two-piece plungers. Typically, higher

well flow rates are the upper operating limit for a continuous flow plunger to start operating. Mechanical models of plunger lifts for drop stage vs. multiphase flow help determine when an operator can deploy plungers in their wells (Sayman *et al.*, 2021). If the plunger lift cycles are aimed at reducing wax buildup, the well can be shut-in for extended periods and the plunger can be allowed to drop to the bottom hole spring even at higher flow rates for a limited number of daily plunger lift cycles.

The hybrid use of plunger and gas lift lifts is common in shale wells in North America. The use of a plunger lift in a well with a continuous gas lift can significantly reduce the rate of gas injection while maintaining or improving the production of liquid and gas from the wellbore. The operation of a plunger lift with a continuous gas supply is called a plunger-assisted gas lift (PAGL). A conventional plunger lift with well shut-in for pressure generation by gas injection is called a gas-assisted plunger lift (GAPL). In a PAGL operation, gas injection primarily affects the pressure gradient, fluid retention and velocity profile of the gas along with the tubing. Taking these effects into account by modelling transient or steady-state multiphase flow allows the use of mechanistic falling and rising models for a continuous flow ram. During GAPL operation, the gas lift typically changes the pressure build-up profile and supports the lift of the plunger. Formation inflow and gas injection must be considered simultaneously to determine the casing inlet pressure in traditional mechanical models of plunger lift. D. Pan (2017) used casing, tubing and line pressures to estimate the rate of upward movement.

Many well-known commercial multiphase flow simulators can evaluate the effect of gas lift on the pressure profile for both tubing and annulus. The nodal analysis capabilities are supported by gas lift sensitivity, which helps in the design and optimisation phases. O. Sayman *et al.* (2020) developed mechanistic models on continuous flow plungers for tested 6-inch and 9-inch two-component plungers with steel, cobalt, and tungsten balls. The study showed that each different plunger geometry changes the plunger resistance characteristics, which affect the lowering and lifting stages of the plunger. This article discusses the peculiarities of using a plunger lift for watered gas wells. The main focus was on the analysis of various parameters that affect the efficiency of plunger systems, including gas pressure, water factor, well depth, and others. The difference between the author's study and the above-mentioned researchers is that a new approach to calculating the optimal cycle time and plunger lifting speed was introduced. A methodology has been developed for determining the upper and lower limits of plunger lift use, which allows increasing the efficiency and reliability of well operation.

Conclusions

The article summarises the peculiarities of operating a watered gas well with a plunger lift and presents the following conclusions. The influence of the water factor on pressure losses in tubing during the movement of a two-phase gas-liquid flow, the gas flow rate coming from the formation and the minimum required gas flow rate for bringing

fluid from the bottom hole to the surface were estimated. A mathematical model has been developed to determine the area of effective use of a plunger lift for removing fluid from the bottomhole of watered gas wells, which depends on the current value of the water factor. The minimum value (lower limit) of the water factor, starting from which it is advisable to use a plunger lift for the operation of a watered gas well, is established. The maximum value (upper limit) of the water factor, above which the energy of reservoir gas is insufficient for the operation of the plunger lift, is substantiated. The model well was tested using a plunger lift at different values of the water factor from 0 to 125 L/thousand m³.

The scope of effective application of the plunger lift is established, which is limited to the values of the water factor in the range from 12 L/thousand m³ up to 41 L/thousand m³. For the maximum value of the water factor, which is 41 L/thousand m³, the width of the gap between the plunger body and the tubing wall should not exceed 0.0025 m. With a wider gap width, the loss of gas coming

from the formation through the gap increases, and the amount of gas remaining becomes less than the required amount of gas to lift the plunger and the well will not operate. It has been established that the efficiency of using a plunger lift for the operation of watered gas wells is influenced not only by the value of the water factor but also by the width of the gap between the plunger body and the wall of the tubing. The proposed methodology for selecting the area of effective use of a plunger lift has been tested for a hypothetical (model) gas well for different values of the water factor (water flow rate). It is advisable to calculate the parameters of the foam packer plunger and compare it with a conventional plunger in further studies.

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Conflict of Interest

None.

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Особливості експлуатації обводненої газової свердловини плунжерним ліфтом

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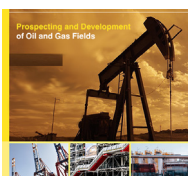
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Анотація. Для отримання високих значень поточного видобутку газу і кінцевого коефіцієнта газовилучення з родовищ за водонапірного режиму необхідно забезпечити повне і безперервне винесення рідини з вибою на поверхню. Ефективним методом інтенсифікації роботи обводнених газових свердловин і продовження періоду їх природного фонтанування є застосування плунжерного піднімача. Мета дослідження – обґрунтування області ефективного застосування плунжерного піднімача для інтенсифікації винесення рідини з обводнених газових свердловин із використанням власної енергії пластового газу залежно від величини водного фактора. Поставлені завдання вирішувалися шляхом проведення досліджень на гіпотетичній (модельній) обводненій газовій свердловині з використанням методів математичного моделювання. Запропонована математична модель роботи плунжерного піднімача апробована для умов гіпотетичної газової свердловини за різних значень водного фактора від 0 до 125 л/тис.м³. Для розглянутої свердловини область ефективного застосування плунжерного піднімача обмежується значеннями водного фактора 12-41 л/тис.м³. Згідно з результатами досліджень обґрунтовано максимальне значення ширину зазору між тілом плунжера і стінкою насосно-компресорних труб, яка не повинна перевищувати 0,0025 м. Розроблена математична модель роботи плунжерного піднімача в обводненій газовій свердловині, яка включає вибір області його ефективного застосування і максимального значення ширини зазору між тілом плунжера й стінкою насосно-компресорних труб, дає можливість забезпечити стабільну роботу обводнених газових свердловин із підвищеним дебітом газу завдяки використанню власної енергії пластового газу і продовжити фонтанний період експлуатації свердловин. У результаті на практиці підвищується поточний видобуток газу і кінцевий коефіцієнт газовилучення з родовища

Ключові слова: продуктивність; водний фактор; механізована експлуатація; мінімально необхідний дебіт газу; область ефективного застосування; ширина зазору



Environmental consequences of gas fields development in the Transcarpathia on the example of Solotvyno Field

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Abstract. The Transcarpathian Trough has a sufficient number of recorded oil and gas manifestations that make it one of the most promising oil and gas bearing areas. The field development is carried out with a large number of wells and is certainly accompanied by a negative impact on the environment. The purpose of the study was to analyse the impact of the Solotvyno Field development on the environment and natural resources of the region, taking into account the geological conditions of the territory and to identify the environmental consequences of the field development. In a narrower sense, this includes the lithological characteristics of all gas-bearing horizons, physical and chemical characteristics of free gas determined by laboratory and field methods, and hydrogeological characteristics. Analytical methods (analysis of literature sources and archive materials) and experimental methods were used in the study. The article deals with the problems of environmental impact of the Solotvyno Gas Field development process. Although the operation of wells is a short-term process and the area of influence is the territory of the drilling site (except for intensive gas flow with open gushing, which is excluded under the accepted drilling technology), the impact of the projected activity on the

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environment is significant. The paper identified the main components of the environment that are most affected by the projected activities. Sources and types of pollutants for each environmental component are identified. Environmental protection measures were proposed and conclusions were drawn regarding the actual impact on the environment of direct production activities. A risk assessment was carried out. The results of the research can be used in practice by oil and gas industry employees, since the impact of the projected activity on the environment is expected

Keywords: oil and gas manifestations; well; environment; risk level; pollutants; laboratory methods; field methods

Introduction

Long-term oil and gas production results in contamination of almost all environmental components by reservoir fluids – oil, gas, and highly mineralised reservoir water. The main possible negative impacts are emissions of pollutants into the air, contamination of groundwater by uncontrolled gas and liquid flows caused by their emissions or spills, leakage of drilling fluids and uncontrolled discharge of waste water. Analysing global trends in science, researchers can focus on the prevalence of studies of environmental impacts of shale gas extraction, as the prospects of shale gas extraction have already been proven by the development of oil shale deposits in Brazil, China and Estonia. As shale gas is a promising resource, the US, China and a number of other countries continue to develop the shale gas industry despite the negative environmental impacts. The COVID-19 pandemic and the current geopolitical situation have forced scientists to suspend most of the research on the environmental assessment of conventional gas fields.

Unlike conventional gas, shale gas is extracted using horizontal drilling and hydraulic fracturing technology. Among the environmentally negative consequences of this method of extraction, N. Zhuravska *et al.* (2023) highlighted the use of a large amount of water resources, which may result in a shortage of drinking water over a period of time. Scientists also pointed out an even greater threat to the environment and public health, namely the exacerbation of chronic diseases and an increase in the number of cancers due to the frequent use of chemical mixtures in hydraulic fracturing. L.I. Pymonenko *et al.* (2023), in their study of the geological factors of shale formations in Ukraine, also noted the increased polluting impact on the environment and the harmful effects on the human body of gas emissions and wastewater from shale processing facilities. However, according to the Energy Security Strategy of Ukraine (Resolution of the Cabinet of Ministers of Ukraine No. 907-r, 2021), the oil and gas sector has seen a significant decline in natural gas production. According to this strategy, one of the goals is to increase natural gas and oil production in an economically justified manner, as well as to reduce Ukraine's dependence on external suppliers. Therefore, Ukraine needs to increase domestic gas production more than ever.

The Transcarpathian Trough has a sufficient number of recorded oil and gas manifestations that make it one of the most promising oil and gas bearing areas. Therefore, one of these fields was chosen to assess the environmental impact of gas field development. In this case, it is a field discovered in 1982. Five wells have been drilled within the field (1-Slt (Slt – Soltvyno), 2-Slt, 6-Slt, 11-Slt

and 68-3-Slt). The field was put into pilot development in 1988. As of the reporting date, two wells are in production (2-Slt, 11-Slt). As of 1 January 2021, gas production totalled 24 million m³. The State Balance Sheet showed initial gas reserves of 371 million m³ (State Balance of Mineral Reserves, 2021). Scientists are actively researching the topic of assessing the environmental impact of the salt mining industry in Soltvyno. For example, S.B. Shekhunova *et al.* (2019) and S.M. Stadnichenko *et al.* (2023) conducted a comprehensive environmental monitoring in the Soltvyno area. Scientists note the difficult geological and environmental situation in Soltvyno and identify a number of potentially dangerous natural and anthropogenic processes such as karst, suffosion, floods, flooding, erosion and landslides. It is worth noting that many of these authors' works are devoted to Soltvyno Salt Dome structures. It is impossible to study the environmental impacts of the Soltvyno Gas Field in isolation from the geo-environmental situation during the development of the Soltvyno Salt Dome.

The environment of the designated site (field) is a part of the natural and industrial complex formed under the influence of agricultural production and industrial facilities of Soltvyno. Therefore, there is a need to assess the environmental impact of the projected activity. Accordingly, the purpose of the study was to assess the environmental impact of the field operation and forecast the development of adverse effects. The main tasks to be solved to achieve the goal were to study the geological structure of the study area, investigate the lithological characteristics of gas-bearing layers and the physical and chemical properties of gas.

Materials and Methods

The Soltvyno Gas Field is administratively located in Tia-chiv District of Transcarpathian Region, on the north-eastern outskirts of the Soltvyno Village (Fig. 1). Literary sources and archive materials were analysed, in particular, the Soltvyno Gas Field development project by Lviv Integrated Research Department of UkrNDIGas, which was aimed at designing a rational development based on the refined geological model of the field based on the results of the Novoselytska formation development and drilling of the 11-Slt production well (FAME, 2002). Recommendations for further development, control and monitoring of development, subsoil and environmental protection are provided. Lithological characteristics of all gas-bearing horizons and physical and chemical characteristics of free gas were determined by laboratory and field methods and hydrogeological characteristics. The field survey methods were carried out as a reconnaissance survey of the

territory and comprised an inspection of the projected wells site, including a description of outcrops, watercourses and groundwater outlets, signs of engineering and geological processes, and a visual inspection of the existing buildings. Reconnaissance surveys are carried out along pre-planned routes (the survey may be combined with route observations). These surveys were carried out to: assess the quality, clarify and supplement the collected materials on the construction area (site); comparative assessment of

engineering and geological conditions at certain options of the construction site and communication routes; preliminary assessment of physical and geological processes and phenomena, as well as possible changes in the geological environment under the influence of construction and operation of the projected facilities; assessment of the complexity of geological conditions, terrain passability and other factors affecting further research, as well as collecting the data required to draw up the work programme.

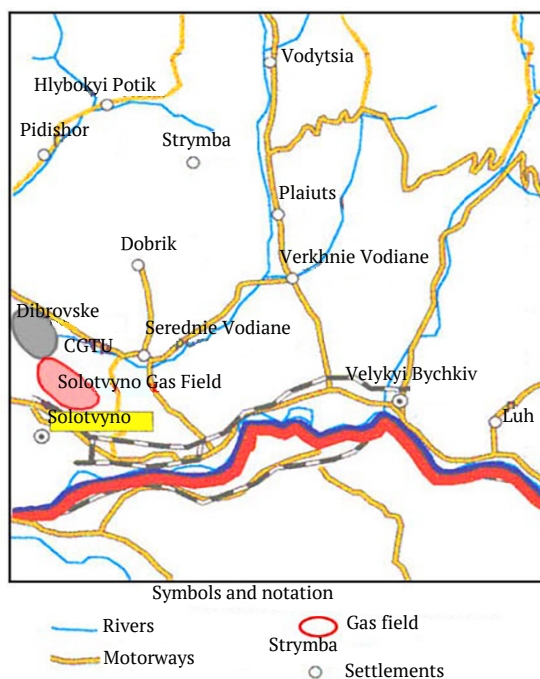


Figure 1. Overview map of the study area

Note: CGTU – complex gas treatment unit

Source: created by the authors

Laboratory research methods were carried out in accordance with GOST 17.1.3.10-83 (1983), GOST 17.1.3.12-86 (1986), DSTU B V.2.1-8-2001 (2001), DBN A.2.2-1-2003 (2003), DSTU ISO 5667-2:2003 (2003), DSTU GOST 27384:2005 (2005), DSTU ISO 15175:2005 (2005), DSTU ISO 10381-5:2009 (2009), DBN V.2.4-3:2010 (2010) and DSTU GOST 17.4.4.02:2019 (2019). They were carried out to determine the classification, physical, strength, deformation and other indicators of soil properties, as well as the chemical properties of groundwater, which are necessary for making design decisions and performing technical calculations. The composition and scope of laboratory work was determined based on both the intended purpose of the survey and the presence of soils with special properties. It was necessary to ensure that at least 10 separate values of physical characteristics and at least six values of strength and deformation characteristics of soil properties are obtained for each selected engineering and geological element. The physical and lithological features of the rocks were determined to determine the lithological and petrographic composition and physical properties. A total of 3 gas samples were taken from gas facilities in the field

in wells 1-Slt, 2-Slt. Gas samples were taken from the gas reservoirs at the wellhead and with downhole samplers during the exploration of gas-bearing and water-bearing horizons. The water samples were studied in the sediments of the Hrushevska Suite of the Paleogene, Tereshul'ska Suite of the Carpathian and Novoselytska Suite of the Badenian in wells 1-Slt, 2-Slt, 6-Slt, 7-Slt, 10-Slt. A total of 28 water samples were analysed for the following parameters: density, mineralisation, sodium, potassium, calcium, magnesium, ammonium, chlorine, sulphate, bicarbonate, carbonates, bromine, iodine, boron, nitrogen oxide, boron oxide, silicon dioxide.

Results and Discussion

According to the goal, it is first necessary to study the geological structure of the study area, investigate the lithological characteristics of gas-bearing layers and the physical and chemical properties of gas. Geomorphologically, the field is located in the southeastern part of the Solotvyno Depression, in the upper reaches of the Tysa River. The depression is bounded to the north by the Carpathian and to the southwest by the Vygorlat-Gutyn Ranges. The terrain

is hilly with a large number of rivers and streams. Cuestas are developed in the area, the formation of which is due to monoclinic layers of conglomerates and sandstones, which are not subject to denudation processes. Absolute elevations range from 250-370 m, with the eastern part of the area being the most elevated (Kravchuk, 2021). The main waterways in the area are the Tysa River and its right tributary, the Apshytsia River. In addition to the Apshytsia River, which flows in the northern part of the area, many small

streams flow into the Tysa River, which mostly dry up in summer. The surface waters are suitable for water supply, fishing, hydropower, and timber processing. The local population uses well and artesian water for food needs. The seismicity of the area is up to 6 points. The construction and climatic zone are normal according to the state construction standards (DBN A.2.2-1-2003, 2003). The geological structure of the field consists of Cretaceous and Paleogene-Neogene deposits (Fig. 2).

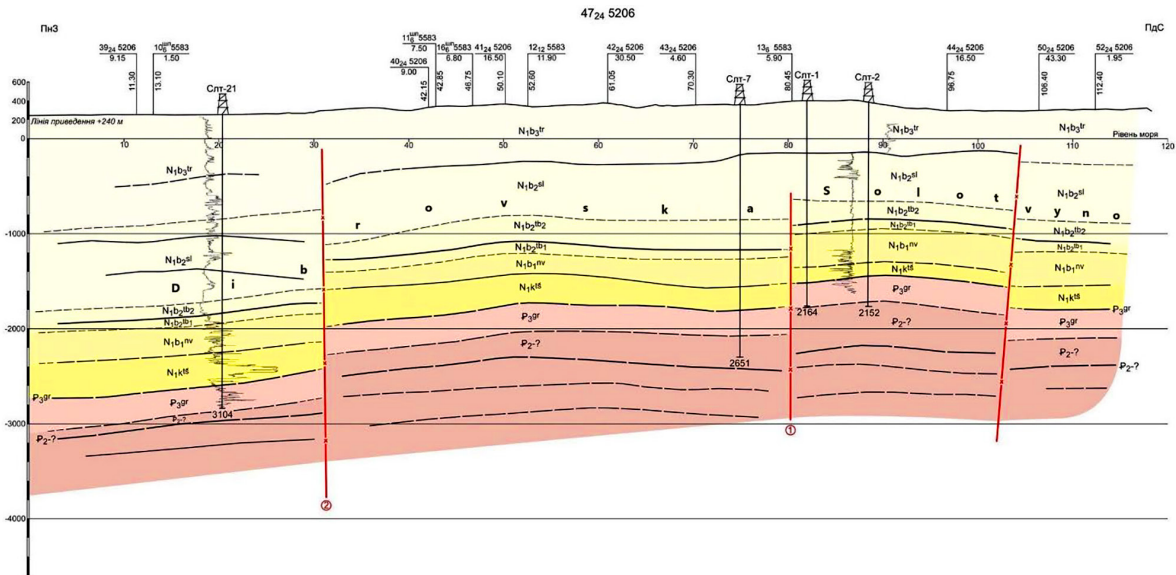


Figure 2. Seismic and geological profile

Source: created by the authors

The Cretaceous deposits within the field and the Soltvyno area as a whole have not been uncovered by drilled wells. They have been studied in neighbouring areas: Tiachevo, Tereblia, Sokirnytsia and others. They are represented by the Krychivska Suite of the Upper Cretaceous, which is composed of interbedded mudstones, sandstones, siltstones, marls and, rarely, limestones. The deposits of the Paleogene system were tapped by wells 1-Slt, 2-Slt, 3-Slt, 4-Slt, 5-Slt, 7-Slt, 8-Slt, 10-Slt. These sediments are dislocated (dip angles reach 50-90°) and are represented by a dark grey thickness consisting mainly of siltstones with marls, sandstones and mudstones interbedded. According to P. Lozyniak & M. Petrashkevich (2007) and P. Lozynjak (2013), this formation was identified in 1989 as the Hrushevaska Suite. Numerous remains of fish scales, fins, and skeletons, single fishes (*Cardium ex. gr. praechinaum hieb*), and pyritised *Spiratella* are found in the sediments of the Hrushevaska Suite. Based on these findings, researchers from the Ukrainian State Geological Research Institute (UkrSGRI) dated the formation to the Oligocene – Lower Miocene.

The siltstones and sandstones are grey and dark grey, dense, carbonate, mica, fine- and medium-grained. The effective thickness of sandstones in well 1-Slt varies from 3 to 8 m according to geological surveys of the wells. Marls are dark grey, black, dense, strong, slightly mica-bearing,

calcareous, obliquely and parallel layered with charred organic remains. The mudstones are dark grey, mica, calcareous, silty. The exposed thickness of the Hrushevaska Formation sediments within the Soltvyno area varies from 65-1,453 m, and within the field from 266-342 m. Two gas deposits of uncertain commercial significance are associated with the Hrushevaska Formation. The Neogene stratigraphic section is presented according to the scheme proposed by UkrSGRI in 1968 (Kruglov & Smirnov, 1968) and revised in 1986 (Burov *et al.*, 1986).

The Neogene system is represented by three layers: the Egenburgian, Carpathian and Badenian. The Egenburgian layer is represented by the Burkalian Suite, which includes sandstones and grey, multi-grained, massive, sandy, clay, siltstones. In the sections of Soltvyno wells, the Burkalian Suite is not faunally distinguished, and it is probably absent in the area. Due to stratigraphic unconformity, the Egenburg overlies the Carpathian layer, which is represented by the Tereshulian Suite at the Soltvyno Field. In the lower part of the formation, colourful conglomerates are developed, composed of poorly sorted pebbles and boulders – grey and white Jurassic and Cretaceous limestones, sandstones and siltstones. Upwards in the section, conglomerates are replaced by grey and greenish-grey sandstones with interbedded quartz siltstones and small amounts of mudstones. The thickness of the formation

ranges from 168–322 m. The Carpathian is stratigraphically unconformably overlain by the Badenian layer, which is represented at the field by the Novoselytska, Tereblyanska, Sotolvynska and Teresvynska Suites.

The Novoselytska Suite has been penetrated by all wells. The lower part is composed of volcanic formations – light greenish-grey tuffs, psamite, siltstone and pelitomorphous, massive, windblown and ash; dark greenish-grey tuffs are aleuuropeanite to psamite, layered, 50% composed of terrigenous pyroclastic fragments. The capacitive characteristic of the volcanic sediments is good, with porosity reaching 11%. The upper part is represented by terrigenous formations – mudstones, siltstones, sandstones, marls with tuff and tuffite interlayers. The thickness of the formation within the Sotolvyno area is 79–384 m, and within the field 79–310 m. Together with tuffs and tuffites, sandy aleurite deposits create good conditions for hydrocarbon accumulation.

The Tereblyanska Suite is believed to be based on the Novoselytsia sediments. According to lithological features, the Tereblyanska Suite is divided into two sub-suites. The Lower Tereblyanska subsuite is represented by a terrigenous stratum of mica, siltstone, sandstone, calcareous sandstone with interlayers of light grey gypsum and anhydrite, tuff-altered siltstone, tuff, and tuff-sandstone. The thickness is 30–151 m. The Upper Tereblyanska subsuite is a rock salt with thin layers and separate clay, siltstone, and sandstone beds ranging in thickness from several cm to several m. The thickness of the subsurface within the deposit varies from 55–295 m. The presence of rock salt in the subsurface makes it a reliable cover (Morozov & Barylo, 2023).

Without any visible stratigraphic discrepancy, the Tereblyanska Suite passes into the Sotolvyno Suite, which has been penetrated by all wells at the field. The Sotolvyno Suite is composed of grey and dark grey mudstone-like siltstone and siltstone clays interbedded with sandstones and siltstones. There are two tuffs, 20–80 m thick, which are exposed in the western direction. The nature of the terrigenous sediments changes in the same direction and becomes more clayey. The thickness of the formation at the field is 574–950 m. The Teresvynska Suite was discovered in wells 1–6-Slt, 7-Slt, 8-Slt, 10-Slt, 11-Slt, 21–23-Slt. Sediments are represented by alternating mudstones, sandstones and siltstones. The thickness of the formation within the Sotolvyno area is 40–752 m, and within the field 254–752 m. Quaternary sediments are widespread at the Sotolvyno Field. These are clays, loams, and shale. The thickness is 0–30 m.

The Sotolvyno Field consists of a single deposit associated with the Novoselytska Suite of the Carpathian, discovered by wells at depths of 1,340–1,530 m. The field is classified as a gas field with produced water. A total of 5 wells have been drilled within the field. Two wells (2-Slt, 11-Slt) are in operation. During the study of the Sotolvyno Field wells, gas samples were taken to obtain data on their physical and chemical composition. The chemical composition and physical properties of gas are shown in Table 1 and Table 2.

Three samples were taken in the Novoselytska Suite sediments. The gas is hydrocarbon, marginal, with the sum

of heavy hydrocarbons equal to 0.08–0.20%. The methane content is 53.86–68.46%, ethane 1.21–2.65%. The gas contains a fairly significant content of nitrogen (14.15–23.06%) and carbon dioxide (4.02–24.68%), which is in line with the findings of A.A. Loktev (2019). Two samples (1-Slt, 2-Slt) contained insignificant levels of helium. The absolute density of the gas is 0.8495–0.8801 kg/m³, and the relative density ranges from 0.7049–0.7303. The lower calorific value of the gas is on average 6,362 kcal/m³ or 26,638 kJ. During the operation, 9 samples were taken from the Novoselytska Suite sediments in the wells. The results of determining the physical and chemical composition of gas are shown in Table 2. A rather sharp change in the composition of the gas sampled during operation in 1-Slt can be explained by both the accuracy of the analyses and the possible inflow of gas portions from previously idle intervals. Helium was not determined in the samples.

Gas from Paleogene sediments was collected and studied in a single sample in 1-Slt (interval 1,842–1,910 m). The gas is dry, methane (91.08%). The ethane content is quite significant (4.52%). Heavy hydrocarbons (pentane + higher) are absent. The content of nitrogen and carbon dioxide is insignificant. It is 1.09% and 0.75%, respectively. Helium was not determined. The lowest calorific value is 8,202 kcal/m³ or 34,342 kJ. The absolute density of the gas is 0.7018 kg/m³, and the relative density is 0.5824. Sotolvyno gas is suitable as a raw material for the petrochemical industry and is high in calories.

The water-bearing objects were studied in the sediments of the Hrushevskaya Suite of the Paleogene, Tereshulskaya Suite of the Carpathian and Novoselytska Suite of the Badenian in wells 1-Slt, 2-Slt, 6-Slt, 7-Slt, 10-Slt. A total of 28 water samples were examined. When testing the deposits of the Hrushevskaya Suite of the Paleogene in wells 7-Slt, 10-Slt, water inflows of 5.52–415.2 m³/day were obtained at a dynamic level of 1,879 m. The reservoir water is predominantly of chlorine-calcium, and sometimes chlorine-magnesium and sodium sulphate type with a density of 1,024–1,103 kg/m³ and salinity of 33.21–120.73 g/l, metamorphosed (rNa/rCl) – 0.93–5.6, chlorine-bromine ratio – 3,179–3,812, calcium prevails over magnesium (rCa/rMg) – 0.96–39.6, sulphation ratio (rSO₄ × 100/rCl) is 1.54–7.15. The content of microelements is as follows: iodine – 1.7–3.22 mg/l, bromine – 3.22–13.3 mg/l. The values of the metamorphisation coefficient indicate hydrogeological closure of the subsoil. The waters of the Paleogene sediments belong to the zone of difficult exchange.

Sediments of the Tereshulian Suite, which are represented by tuffs and conglomerates, were studied in wells 2-Slt, 7-Slt, and 10-Slt. During their testing, water inflows of 0.6–12.09 m³/day were obtained at dynamic levels of 1,420 and 752.5 m, respectively. Formation waters are mainly of chlorine-calcium, sometimes sodium sulphate type with salinity of 10–174 g/l, metamorphosed (rNa/rCl) – 0.74–1.02, calcium prevails over magnesium (rCa/rMg) – 1.7–30.6, sulphation coefficient (rSO₄ × 100/rCl) is 0.23–11.7. Micro components include bromine and iodine. Their content is respectively: bromine – 4.4–25.4 mg/l; iodine 0.4–6.4 mg/l.

Table 1. Characteristics of free gas

Reservoir deposit	Well No.	Test interval, m absolute mark	Reservoir pressure critical pressure MPa	Reservoir temperature critical temperature K	The reduced pressure	The coefficient of supercompressibility fraction of a unit	Corrections, fraction of a unit		Density kg/m ³ absolute relative	Mole content, g/cm ³															
							for deviations from the Boyle-Mariotte law	for temperature		methane	ethane	propane	iso-butane	H-butane	pentane + higher	helium	argon	carbon dioxide	nitrogen	paraffin wax	other related useful components				
N ₁ nv	1-Slt	1,550-1,440 -1,134.1- 1,044.2	14.45 4.81	340 202	3.0	0.877	1.14	0.86	0.8801 0.7303	53.86	2.65	1.34	0.32	0.41	0.20	0.01	-	18.14	23.06	-	-	-	-	-	-
										61.51	1.21	0.62	0.25	0.23	0.08	0.001	-	22.04	14.15	-	-	-	-	-	-
N ₁ nv	2-Slt	1,550-1,502 -1,117.4- 1,042.4	14.52 5.07	341 212	2.82	0.845	1.18	0.86	0.8593 0.7137	57.04	1.91	0.83	0.23	0.26	0.19	-	-	24.68	14.88	-	-	-	-	-	-
										57.47	1.93	0.93	0.27	0.30	0.16	-	-	17.36	21.62	-	-	-	-	-	-
average for the deposit																									
φ	1-Slt	1,910-1,842 -1,514- 1,446.1	14.62 14.62	350 201	3.2	0.861	1.16	0.84	0.7018 0.5824	91.08	4.52	1.87	0.22	0.47	-	-	-	0.75	1.09	-	-	-	-	-	-

Note: N₁nv – Novoselytska Suite of Miocene; φ – Palaeogene; 2-Slt – no helium content at depth interval 1,550-1,502

Source: created by the authors

Table 2. Characteristics of free gas in the development process

Reservoir deposit	Well No.	Test interval, m absolute mark	Density kg/m ³ absolute relative	Mole content, g/cm ³											
				methane	ethane	propane	butane	pentane + higher	hydrogen sulphide	helium	argon	carbon dioxide	nitrogen	paraffin wax	other related useful components
N ₁ nv	1-Slt	1,530-1,440 -1,134.1- 1,044.2	0.9917 0.8230	65.48	1.20	0.44	0.23	0.13	-	was not determined	-	21.0	11.52	-	-
		"-	0.9952 0.8252	62.21	1.19	0.45	0.53	0.10	-	"-	-	21.4	11.42	-	-
		"-	0.8673 0.7198	79.04	1.49	0.50	0.22	0.04	-	"-	-	13.44	4.37	-	-
		"-	0.7747 0.6429	85.95	1.56	0.54	0.29	0.13	-	"-	-	3.56	7.97	-	-
		"-	0.9125 0.7438	73.65	1.92	0.56	1.43	0.13	-	"-	-	12.82	15.27	-	-
		"-	0.9505 0.7808	73.33	1.512	0.457	0.129	0.393	-	"-	-	15.27	9.07	-	-
N ₁ nv	2-Slt	1,467-1,445 -1,055.2- 1,033.4	- 0.721	77.866	1.976	0.427	0.267	-	-	-	-	7.896	11.896		
		"-	- 0.711	77.866	1.976	0.427	0.267	-	-	-	-	7.896	11.896		
		"-	0.917 0.761	73.977	1.433	0.465	0.214	0.217	-	"-	-	15.863	7.850	-	-
		"-	0.876 0.726	76.567	1.382	0.371	0.149	0.146	-	"-	-	11.967	9.418	-	-
		"-	0.974 0.809	67.224	1.435	0.469	0.235	0.220	-	"-	-	19.250	11.617	-	-
		"-	- 0.786	73.587	1.555	0.474	0.236	-	-	-	-	12.153	11.747		
N ₁ nv	11-Slt	1,467-1,366 -1,075.2- 974.2	- 0.711	68.735	1.578	0.479	0.107	0.370	-	-	-	18.018	10.685		
N ₁ nv	68-3-Slt		- 0.711	68.46	1.47	0.33	0.09	-	-	-	-	4.02	25.63		

Note: N₁nv – Novoselytska Suite of Miocene

Source: created by the authors

The reservoir waters of the Novoselytske deposits have been studied the most. During their testing in wells 1-Slt, 2-Slt, 6-Slt, 7-Slt, 10-Slt, water inflows of 7.2-72 m³/day were obtained at dynamic levels of 165-860.5 m. Formation waters are mainly of chlorine-calcium type, and sometimes of sodium bicarbonate, sodium sulfate and chlorine-magnesium type with mineralisation of 18.6-180.3 g/l and density of 1,010-1,122 kg/m³, the metamorphosis ratio (rNa/rCl) is 0.6-1.13, calcium prevails over magnesium (rCa/rMg) – 0.47-54.99, chlorine-bromine ratio ranges from 648.8 to 62,941.5, sulphation ratio (rSO₄ × 100/rCl) – 0.04-7.79. Content of micro components: Br – 3.3-120 mg/l; iodine – 0.4-5.08 mg/l. The high metamorphisation and mineralisation of the Novoselytska Suite waters indicate that the field is located in a zone of difficult exchange.

The water enrichment of the host sediments depends mainly on their reservoir properties. Water salinity increases with depth. No other patterns of change can be found in the section or in the blocks. The reservoirs in the Novoselytsia Formation are tuffs, tuffites and sandstones. Clays and salts of the Tereblyanska Suite are the regional reservoir cover for the Novoselytsia Suite. In the saline Upper Tereblyanska Subsuite and Teresvynska Suite, according to geological wells, the horizons are associated with sandstone and siltstone layers. These deposits have not been tested at the field. The field itself is divided into separate blocks by a system of transverse and longitudinal faults, and the reservoir waters of these blocks differ in chemical composition, although it is not possible to identify the patterns of this difference.

Technogenic load on the landscape is created by: residential development of Sotolvyno settlement; road network; power and communication lines; gas transmission network; two production wells with a depth of 1,580-1,252 m. The Sotolvyno Field, as an object of technogenic environmental impact, consists of: two production wells (2-Slt, 11-Slt) with a depth of 1,580-2,152 m designed to extract gas from the subsoil; plumes with a diameter of 114×10 mm and 114×6 mm and a length of 680 m and 250 m. At the Sotolvyno Field, gas is collected, treated and supplied according to the following scheme (Fig. 3).

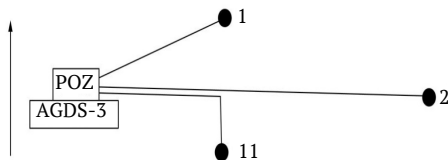


Figure 3. Sotolvyno Field gas collection scheme

Note: AGDS – automatic gas distribution station
Source: created by the authors based on FAME (2002)

Gas from production wells 2-Slt and 11-Slt is supplied to the Sotolvyno Gas Pre-Treatment Unit via individual pipelines with diameters of 114×10 and 114×6 mm and lengths of 680 and 250 m, respectively (Fig. 4).

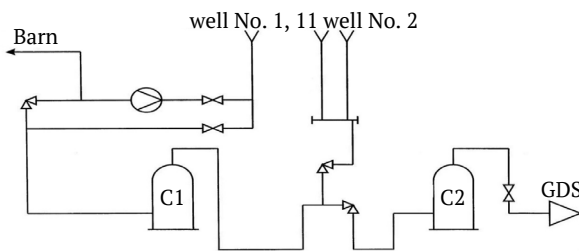


Figure 4. Sotolvyno Gas Pre-Treatment Unit

Source: created by the authors based on FAME (2002)

As a processing company, the production complex consumes the following natural resources: natural gas (dry or water-gas mixture) from deep deposits; electricity for lighting and electrical equipment at the GTU; water, which is consumed only to fill heating radiators at the GTU and maintain a constant fire-fighting reserve of 150 m³. Water

is supplied by tanker trucks. The gas field products are gas purified in accordance with the requirements of the state standard, and the wastes are associated formation water (AFW), regeneration gas and minor emissions of gas and combustion products. In this regard, gas production at Sotolvyno Field worsens the environment due to the following.

Gas production: each production well is a technological source of permanent damage to the subsoil with irreversible consequences – depleted natural gas deposits cannot be restored. Gas emissions from venting through the spark plugs of the GTU gearboxes and through the flare nozzles of wells during their repair: the locations of these emissions are technological sources of intermittent gas pollution with eliminable impacts – the air is self-purified between individual emissions. Emissions of gas combustion products through the chimneys of the boiler room, the gas metering station boiler, the fire pump boiler, the gas heater and the emergency motor generator are permanent sources of continuous air pollution (Kryvenko, 2020).
Emergency gas emissions: temporary sources of pollution or, in the case of spontaneous combustion, environmental damage. After the accident is eliminated, the air is self-purified and the damaged areas are reclaimed.

The negative impact of Sotolvyno gas production complex on the environment during operation is limited to the subsoil and atmosphere. There are no sources of direct impact on the hydrosphere and biosphere in the production process. The impact on the social sphere is positive (SOU 73.1-41-11.00.01:2005, 2005). The impact of gas extraction on the geological environment in the subsoil extends beyond the well casing only to the deposits. Due to gas extraction, the reservoir pressure in the deposits will decrease from the initial 4.8 MPa to the residual 0.3-0.1 MPa. The volume of the environment with a damaged gas-dynamic regime is currently ~20 million m³. The atmosphere is polluted by permanent (chimneys of the operator’s room boiler room, gas metering boiler, fire pump boiler, gas heater), emergency (motor generator chimney), and periodic (“spark plugs” at the GTU outlets) sources located on the GTU territory. Characteristics of the main harmful substances emitted into the atmosphere by gas and industrial facilities are shown in Table 3. The values of the estimated emissions of harmful substances from the field development facilities can be considered as maximum permissible concentrations (MPC).

Table 3. Characteristics of the main harmful substances emitted into the atmosphere

Name of the harmful substance	Maximum single MPC, mg/m ³		Hazard class	Aggregate state
	MPC of harmful substances in the air of settlements	MPC of harmful substances in the air of work areas		
Nitrogen oxide	0.4	5.0	3	gas
Nitrogen dioxide	0.085	5.0	3	gas
Carbon monoxide	5.0	20	3	gas
Saturated hydrocarbons C ₁ -C ₃ (methane, ethane, propane)	50 (approximate safe exposure level for methane)	300	4	gas
Saturated hydrocarbons C ₄ -C ₆ (butane, pentane, hexane)	200	300	4	gas
	100	300	4	vapours
	60	300	4	vapours
Soot	0.15	4.0	3	suspended solids

Source: created by the authors

When performing air pollution calculations for the most typical air pollutant gradients, the limit of surface concentrations from industrial emissions of 0.4 MPC is assumed. The results of air pollution calculations for some fields operating in the operational mode, performed by UkrNDGI Open Joint Stock Company, show that the concentration of harmful substances at the border of the sanitary protection zone of the facilities does not exceed 0.26 MPC. Based on practical measurements at Ukrnafta's wells, the maximum amount of emissions per well during the test is as follows: carbon monoxide – 4 kg; hydrocarbons – 5 kg; nitrogen dioxide – 1 kg; soot – 2 kg; sulphur dioxide – 1 kg. Based on the above data and actual measurements at Ukrnafta's drilling sites and group collection points, the following conclusions can be drawn: no local air pollution occurs; dispersion of harmful substances occurs entirely in the residential area. The hazard category of the enterprise according to the environmental protection classification (OND-84) is not lower than 2.

As noted by the scientists of the Ivano-Frankivsk National Technical University of Oil and Gas L. Poberezhna *et al.* (2022), a key group of indicators affecting the environmental safety of man-made facilities, including oil and gas wells, is the quality of technical means. The construction of oil and gas wells and their subsequent operation are accompanied by a variety of equipment that is essential for trouble-free operation. Additional risks associated with the failure of oil and gas equipment are caused by its long service life. Product quality is characterised by both quantitative and qualitative indicators that affect the environmental impact of oil and gas well construction and include design characteristics, reliability, efficiency of use of raw materials, fuel and energy, manufacturability, transportation, environmental aspects, and safety. These indicators can directly or indirectly affect the risks of hazardous situations, highlighting the importance of their monitoring and management to ensure environmental safety in the oil and gas industry. Effective management of technical equipment quality indicators is critical to reducing the risks associated with the environmental safety of oil and gas wells, which in turn contributes to environmental protection and accident prevention.

Scientists O. Mishchenko & A. Pelts (2019) analysed the prospects for the further functioning of the Lokachi Gas Field. The article noted that despite the negative impact on the environment, it is advisable to further develop this field. The proposed measures for the further functioning of the gas production system of the Lokachi District reduce the harmful impact on the environment. Given the similarity of the high level of complexity of the environmental situation at the Lokachi Gas Field and the Solotvyno Gas Field, the authors can adopt the experience of their colleagues and supplement it with proposals based on the results obtained.

Analytical studies of oil and gas well construction processes, including their environmental aspects, were conducted by A. Pavlychenko *et al.* (2023) according to a clearly defined methodology. This methodology includes the formulation of the problem, development of

mathematical and physical models, selection of a solution method, computational experiment, laboratory research, and analysis of the results. It is important to note that land plots for drilling are provided for temporary use and must be returned in a condition suitable for agriculture. From an environmental point of view, drilling affects the geological environment, disrupting its normal state. To avoid negative consequences, it is recommended to use rational well designs that ensure consistent overlap of drilled intervals.

M.A. Caretta *et al.* (2024) mediated the risks with a number of benefits that further extraction is expected to bring. In addition to the general negative impact on the environment, this article examined in detail how energy infrastructure projects aimed at extracting minerals negatively affect local residents, their identity and sense of belonging to a particular area. In particular, the article focused on the protest of the indigenous population of Virginia against the extraction of minerals on their territory, which threatens their sense of place and identity. T. Yatsyshyn (2021) proposed the development of a system that would help reduce the development of environmentally hazardous processes at different stages of the life cycle of oil and gas production facilities. However, this development, in the opinion of the authors of the current study, is more appropriate to apply at the stage of well drilling. At this stage of the study, the goal is to address the issue of reducing the negative environmental impact of the operation of existing wells.

One of the methods of environmental monitoring proposed by V.Ye. Filipovych *et al.* (2020) is remote sensing of the Earth in the area of hydrocarbon production. The scientists have proven the effectiveness of this method on the example of Boryslav and proposed a scheme for remote environmental monitoring at oil and gas facilities with the study of hydrocarbon pollution of the geological environment. They noted that the results of this method should be used to study subsidence, flooding of groundwater and the production area, migration of pollutants along tectonically weakened zones and zones of increased rock fracturing. Since the list of these hazardous processes is also relevant for the area studied in this paper, the remote monitoring method can be recommended for use in the Solotvyno Gas Field.

The article by G. Gorvanko *et al.* (2021) argued that due to the increasing anthropogenic load and negative impact on natural processes in the Transcarpathian Region, there is an urgent need to develop comprehensive environmental protection measures to preserve the river system of the region. The natural potential of water resources and the economic potential of the Transcarpathian Region allow to identify key areas for their use and protection. Rivers, temporary watercourses and reservoirs for water purification and water supply and irrigation should be included. Particular attention should be paid to protecting the river system from deluges and floods that occur periodically in the region. Based on the analysis and after reviewing the research results of the above scientists and comparing them with current results, the prospects of production at Solotvyno Gas Field should be

discussed and further possible options for reducing the negative impact on the environment can be suggested. The Soltvyno Field is located in the valley of the Tysa River and its tributaries. Therefore, surface waters require protection from the products of gas production processes. In addition, surface waters are connected to the waters of the upper part of the geological section, which are used as drinking water. Potential sources of surface and drinking water contamination include: working fluids used in underground and workover operations and methods of stimulating gas flow to wells; chemicals and reagents used in well workovers and methods of stimulating gas flow to wells; contaminated rainwaters.

To prevent contamination of surface, ground and drinking water, it is necessary to use a closed system of working fluid circulation during well workovers with the collection of sludge and well flushing products and their removal for neutralisation and destruction; use a closed system of bottomhole treatment with the collection of treatment products and their removal for neutralisation and purification; store chemicals for treating well bottomhole zones and combating complications during their operation in sealed containers; maintain cleanliness in the areas near the wellhead and at gas treatment facilities, and timely clean up and decontaminate contaminated areas. A special factor of possible environmental impact is the mixture of condensate moisture and AFW that is carried out of the well. According to the experience of development of Baden gas deposits in the Outer Zone (Hrynivske, Kadobnianske, Bohorodchanske), the amount of AFW is not significant and can be up to 5-10 m³ per year. It is recommended to dispose of the Soltvyno Field's AFW in the contour part of the Vygodske Deposit of the Bytkiv-Babchenske Gas Condensate Field (absorption wells 24-Bt (Bt – Bytkivska), 478-Bt). Delivery of AFW for injection into the absorption wells (24-Bt, 278-Bt) is planned by road.

Accidents in the gas industry are associated with depressurisation of the technological scheme, and therefore cannot influence the intensity and degree of impact of all the identified sources. In the event of an accident, a new source of gas pollution arises – the place of depressurisation. The emergency gas release lasts from the moment the accident occurs until the gas flow is shut off. After the accident is eliminated, the air above the accident site is self-purified. The Soltvyno Field is planned to be developed for pilot and commercial production of natural gas. There is 1 horizon under development, which is operated by two wells. To prevent soil contamination, the following measures are envisaged: selection of sites and routes for structures and communications only on alienated lands; rational placement of equipment on the territory; covering the equipment sites with resistant materials; equipment of special places for dosing reagents, where these reagents do not enter the soil; hydraulic pressure testing of pipelines before their commissioning; corrosion protection of pipelines; use of a sealed system for collection, preparation, accounting and treatment of waste water. To protect groundwater, the following measures are proposed to

prevent groundwater contamination: sealing of equipment; insulation of underground pipelines with bitumen-rubber insulation; installation of curbs and improvement of pavement at sites; collection of surface wastewater from sites bounded by curbs (methanol tanks, gas dehydration units); designation and observance of sanitary protection zones; control of groundwater quality near underground tanks.

The comprehensive environmental impact assessment of the proposed activity and the assessment of the impact on each environmental component showed the following. Taking into account that well operation is a short-term process, the area of influence of which is the territory of the drilling site (except for intensive gas flow with open fountain, which is excluded under the adopted drilling technology), the impact of the planned activity on the environment will be minimal. The parameters of harmful impact of the planned activity on the environment will not exceed the regulatory indicators, provided that the proposed measures aimed at minimising the environmental impact and preventing the exceeding of the established standards are followed. Compliance with these requirements, as well as continuous supervision and control over the technological process and timely implementation of environmental protection measures, will help to minimise the environmental impact.

Conclusions

Due to the sufficient number of wells for the Soltvyno Field development, it was necessary to analyse the impact of the field development on the environment and natural resources, study the geological conditions of the territory and identify the environmental impact of the field development. The study of the geological structure of the Soltvyno Field revealed the gas content of the Novoselytska Suite of the Carpathian Formation, which was tapped by wells at depths of 1,340-1,530 m. Technogenic load on the landscape is created by: residential development of Soltvyno Village; road network; power and communication lines; gas transmission network; two production wells with a depth of 1,580-1,252 m. The environmental impact assessment of the planned activities, as well as the impact on certain elements of nature, was analysed in accordance with the state construction standards.

Taking into account that well operation is a temporary process limited to the drilling site (except for cases of intensive gas production with open-flow, which is excluded if the accepted drilling technology is used), the environmental impact of the planned activities is expected to be minimal. The indicators of negative impact of the planned activities on the environment will not exceed the regulatory values if the proposed measures aimed at reducing the environmental impact and preventing the exceeding of the established standards are followed. Fulfilment of these requirements, as well as constant supervision and control of the technological process and timely implementation of environmental protection measures, will reduce the environmental impact to a minimum level. In the future, further research is planned to expand the study area and assess the negative environmental impact of other gas

fields in the western region. The aim will be to provide a comprehensive and accurate study of environmental impacts, recommend new ways to reduce the negative environmental impact of gas production and ensure maximum benefit at minimum cost.

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None.

Conflict of Interest

None.

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Екологічні наслідки експлуатації газових родовищ Закарпаття на прикладі Солотвинського родовища

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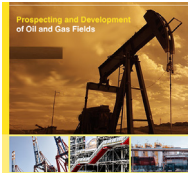
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Анотація. У Закарпатському прогині налічується достатня кількість зафіксованих нафтогазопровів, які дають змогу ставити його в ряд перспективних нафтогазоносних областей. Розробка родовища проводиться великою кількістю свердловин та безумовно супроводжується негативним впливом на навколишнє середовище. Метою дослідження було проаналізувати вплив експлуатації Солотвинського родовища на стан навколишнього середовища й природних ресурсів регіону зважаючи на геологічні умови території та виявлення екологічних наслідків експлуатації родовища. У більш вузькому значенні – це літологічна характеристика всіх газоносних горизонтів, визначена лабораторними та польовими методами фізико-хімічна характеристика вільного газу, гідрогеологічна характеристика. У роботі використовувались аналітичні методи (аналіз літературних джерел та фондових матеріалів) та експериментальні. У статті розглянуто проблеми впливу на навколишнє середовище процесу експлуатації Солотвинського газового родовища. Хоч експлуатація свердловин є процес не довготривалий і зоною впливу є територія бурового майданчика (за винятком інтенсивного газопроявлення із відкритим фонтануванням, яке при дотриманні прийнятої технології буріння виключається), вплив проектованої діяльності на навколишнє середовище значний. У роботі виділено головні складові навколишнього середовища, на які створюється найбільший вплив прогнозованої діяльності. Виділено джерела та типи забруднювачів відносно кожної складової природи. Запропоновано природоохоронні заходи й зроблено висновки відносно реального впливу на середовище прямої виробничої діяльності. Оцінено ступінь ризику. Результати дослідження можуть бути використані на практиці працівниками нафтогазової промисловості, оскільки вплив проектованої діяльності на навколишнє середовище очікуваний

Ключові слова: нафтогазопрові; свердловина; навколишнє середовище; ступінь ризику; забруднювачі; лабораторні методи; польові методи



Peculiarities of late-stage development of oil fields in Ukraine and ways of increasing oil production

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Abstract. The relevance of the study lies in identifying typical stages of oil field development and determining the beginning of the late-stage period based on the actual values of annual and accumulated oil production and water cut of well products. The purpose of the research was to identify the main features of the late stage of development and to develop technical and economic directions and measures to stabilise and increase oil and gas production. The paper analysed the possibilities of increasing domestic oil production in Ukraine by using the resource potential of fields whose reserves are classified as hard-to-recover. The authors formulated the criteria by which individual deposits and fields contain hard-to-recover reserves and determined the structure of such reserves, taking into account the elements of residual oil saturation of the pore space. The peculiarities of late-stage field development in terms of the dynamics of changes in development indicators were determined. The geological, industrial, economic, social and environmental problems accompanying the development of fields at a late stage were considered. Using the example of the development of the oil industry in Ukraine, the article analysed typical stages of field development and oil and gas production. The structure of oil reserves classified into active reserves, which are extracted mainly through natural reservoir energy, and hard-to-recover reserves, which require the use of targeted artificial stimulation of the reservoir system using various targeted methods and technologies, was presented. A procedure for determining the beginning of the late stage of field development based on the curves of actual accumulated oil production and water cut of well products was proposed and demonstrated using real actual data. The location of the residual hard-to-recover reserves in the oil-saturated pore space was identified. Based on the available average statistical information, the defining features of the late stage of development were comprehensively

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disclosed, which are grouped into geological, technological, organisational, economic, financial, social and environmental. The main areas of activity of research and development and oil and gas companies to address the problem of stabilising and increasing oil production at the late stages of field development were identified

Keywords: oil fields; development indicators; hard-to-recover reserves; residual oil; oil recovery; production increase

Introduction

In the current energy situation in Ukraine, which is characterised by growing demand for hydrocarbons and limited opportunities to discover new large fields, the issue of optimising oil production is extremely important. This is especially true for fields that are at late stages of development, when their natural production potential is significantly reduced and the economic viability of operation requires the implementation of additional technical and technological measures. The late stage of oil field development, which occurs after the stage of maximum production, is characterised by a slow decline in production, high water cut and the need to apply effective methods to maintain technological and economic efficiency of production. Ukraine, which has limited domestic hydrocarbon reserves, is largely dependent on energy imports, which requires special attention to the efficient use of the resource potential of existing fields. The majority of Ukraine's oil fields are in the fourth or late stages of development, with over 90% of wells operated by mechanised production methods and a significant decline in average well production rates. In such circumstances, it is particularly important to develop and implement targeted oil recovery technologies that will increase production volumes and extend the life of the fields. Late-stage field development is also accompanied by problems that cover not only technical but also economic, environmental, social and ecological aspects. Loss of equipment integrity, increased levels of gas pollution, and physical 'aging' of industrial facilities create additional problems for both the economic performance of enterprises and environmental risks.

A number of publications have been devoted to the study of the late stage of oil field development. Their main focus is to consider individual fragments of the field development process without generalising them as a whole. The works of I. Petrenko *et al.* (2021) and V. Moiseiev (2023) mainly covered the issues of the state of production indicators and methods of stimulating hydrocarbon inflow into wells, limiting water flow paths, and levelling the injection profile in injection wells. In particular, scientists I.M. Petrenko *et al.* (2021) identified ways to improve the economic efficiency of oil production enterprises. V. Moiseiev (2023) noted that one of the problems is the lack of oil refining capacity. Almost all oil refineries (about 10) have been shut down since independence, with the exception of two – Kremenchuk and Shebelynka. However, the war between Russia and Ukraine has had serious consequences for them. The study by I. Cuper & A. Uhrynovskiy (2018) presented the structure forms and components of pore space saturation. The authors discussed the physical and chemical characteristics of reservoir hydrocarbons and water, phase changes in hydrocarbon systems, surface and molecular processes occurring at the interface. The article

also explained the parameters of hydrocarbon recovery, energy states and operating modes of oil and gas reservoirs, physical fundamentals, and the use of advanced methods of oil and gas condensate recovery.

The paper by A.A. Isaev *et al.* (2022) provided information on methods of stabilising oil production, reducing water cut and preventing its growth, as well as on traditional methods of increasing development efficiency. The paper also presented a set of measures aimed at improving the efficiency of the Zarechnoe field development in the Republic of Tatarstan. M.U. Tahir *et al.* (2023) modelled a number of strategies using water, gas and chemical injection methods to improve production results: they analysed methods of enhanced oil recovery by gas injection, thermal and chemical treatments of the reservoir system. The researchers presented a reliable, comprehensive screening method aimed at optimising the production of "old" oil fields.

The above studies lack a comprehensive approach to solving the problem of increasing oil production at the late stage of development, taking into account economic and environmental indicators. Efficient operation of late-stage fields requires the use of innovative technologies, such as flow-deviating methods, infill drilling, aquifer plugging, and elimination of leakage in the wellbore space. The aim of this study was to identify the defining features of the late stage of oil field development and to formulate technical, economic and geological and industrial measures that will help stabilise and increase oil production. The focus is on hard-to-recover reserves, for which traditional methods are not always effective.

Materials and Methods

This paper provided a detailed analysis of all active oil fields in Ukraine that are at a late stage of development according to the State Committee of the Oil, Gas, and Oil Refining Industry of Ukraine (1997) and M. Ivaniuta (1998). The most attention was paid to the fields that are on the balance sheet of the main oil producing company, Public Joint Stock Company Ukrnafta (PJSC Ukrnafta), and are among the most important sources of hydrocarbon production in Ukraine, such as Hlynsko-Rozbyshivske, Bugruvativske, Leliakivske, Hnidentsivske, Dolynske, Bytkivske, and Boryslavsk. These fields were selected based on high oil production, water cut and the presence of residual hard-to-recover reserves, which is typical for the final stage of development.

The available information on production volumes, flow rates and water cut rates was grouped into several categories based on key geological, production and technological characteristics. This grouping made it possible to determine the structure of the remaining oil reserves that require

special methods for their recovery. The main criterion indicators are based on those specified by V.S. Boyko *et al.* (1996), V.S. Boyko (2012) and V.P. Gryshanenko *et al.* (2015): the level of water cut of well products, which is one of the indicative factors of the late stage of oil field development; the type and structure of residual oil saturation of the pore space, which determines the potential of undeveloped hard-to-recover reserves; distribution by types of reserves, in particular, the allocation of active reserves produced under natural conditions and hard-to-recover reserves that require the use of targeted stimulation methods.

To build the architecture of the main features, a set of parameters reflecting typical characteristics of the late stage of development was formed. They include the following groups of indicators: geological (structure of residual reserves, pore space heterogeneity, presence of low-permeability layers); technological (well operation methods, flow rates, water cut); economic (production cost, profitability, investments in the implementation of production stimulation methods); environmental (level of environmental pollution). Initial information was collected from the following sources: State Committee of the Oil, Gas, and Oil Refining Industry of Ukraine (1997) and V. Moiseiev (2023), which contain data on the total number of oil fields, dynamics of oil, gas and water production. Scientific and technical literature listed in the references was also used. Microsoft Excel was used for statistical analysis and modelling, which made it possible to group data, build water cut and cumulative production graphs, build an architecture of late-stage development features and determine its beginning in technological and time space. Thus, an integrated

approach that combined statistical analysis and geological modelling made it possible to assess the state of late-stage development of the fields and propose specific measures to improve the efficiency and completeness of oil production.

Results and Discussion

Ukraine does not have sufficient domestic oil reserves. There is also no reason to assume that it will be provided with sufficient oil in the future (Lukin, 2008; Vytvytskyi & Pilka, 2016). According to V. Moiseiev (2023), in 2020, there were 216 oil fields in Ukraine, of which 193 were very small with oil reserves of up to 1 million tonnes. There are 21 fields with small reserves (1-5 million tonnes), Bugruvativske field with small reserves, and Hlynsko-Rozbyshivske field with medium reserves (5-30 million tonnes) (State Committee of the Oil, Gas, and Oil Refining Industry of Ukraine, 1997; Ivaniuta, 1998). About 45% of the total well stock operates with weighted average flow rates of up to 1 tonne per day and produces about 3% of oil from the total production. An analysis and summary of the development of the oil industry in Ukraine, based on the example of the largest oil and gas company PJSC Ukrnafta (produces 86% of oil, 28% of gas condensate, and 16% of gas from total hydrocarbon production in Ukraine), shows that it has passed the period of maximum production, which is inevitably followed by a decline (Lukin, 2008; Vytvytskyi & Pilka, 2016). Figure 1 shows the dynamics of annual and cumulative oil production and water cut rates, built by the authors based on actual data of PJSC Ukrnafta, which has a classical character similar to the world oil production curve proposed by K. Hubbert (1956).

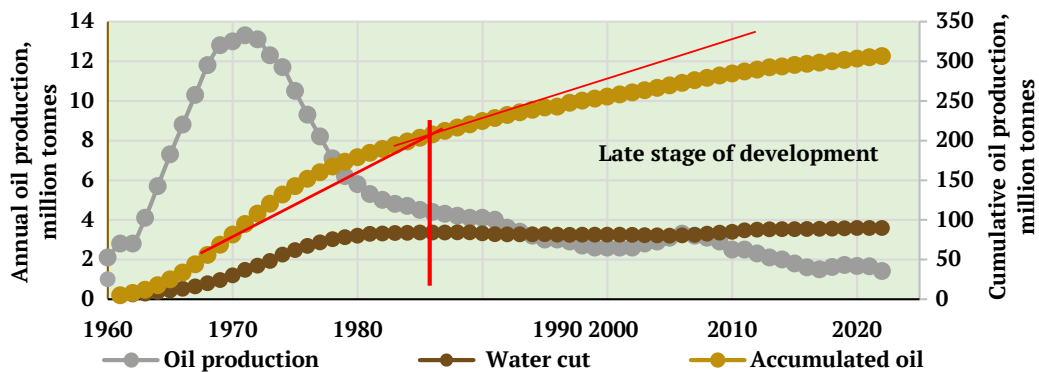


Figure 1. Dynamics of oil production and water cut of well products by fields of PJSC Ukrnafta

Source: created by the authors based on actual data of oil extraction enterprises

The decline in production is mainly due to intensive depletion of reserves at the main fields and their transition to the late stages of development. The maximum annual oil production was achieved in 1972 due to the discovery and accelerated development of relatively large fields with significant reserves, such as Hlynsko-Rozbyshivske, Bugruvativske, Korzhivske, Leliakivske, Hnidentsivske (eastern region), Dolynske, Pivnichno-Dolynske, Strutynske, Oriv-Ulychnianske, Starosambirsk (western region) and others (State Committee of the Oil, Gas, and Oil Refining Industry

of Ukraine, 1997; Ivaniuta, 1998; Gryshanenko *et al.*, 2015). Since 1972, oil production has been steadily declining. In 1976-1982, the rate of decline was 8.5-12%, in 1985-1991 – 2.0-2.2% per year. After 1992, these rates increased to 5-10%.

There are four stages of oil field development (Boyko *et al.*, 1996; Oil and Gas Institute, 2004; Gryshanenko *et al.*, 2015). Figure 1 identified these stages as: I – increasing oil production; II – stable production; III – declining production; IV – late stage, which is the longest and is characterised by low, slowly declining levels of oil production,

high water cut of wells, and their conversion to mechanised methods of operation. In Ukraine's late-stage fields, about 90% of wells are operated with pumps of various types and sizes, and about 70% of wells have oil production rates of up to 2 tonnes per day.

The first three stages constitute the main development period lasting, as a rule, 25-30 years, during which 70-85% of recoverable oil reserves are extracted, the remaining 15-30% of recoverable reserves are extracted at

the IV or late stage. The authors propose to determine the conventional beginning of the late stage by the curves of accumulated oil production and water cut, which, according to the graphic construction, for Ukrnafta's fields corresponds to 2008 (Fig. 1). The predominant share of oil reserves produced at the late stage of development consists of hard-to-recover reserves (Fig. 2), the extraction of which requires diverse and unique methods and technologies of impact on the reservoir system.

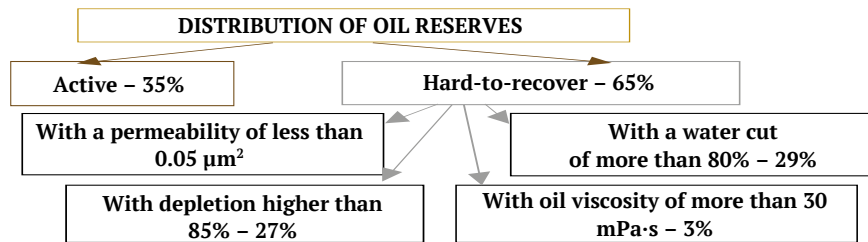


Figure 2. Qualitative characteristics of recoverable reserves

Source: created by the authors based on T.D. Van Golf-Racht (1982), V.S. Ivanyshyn (2003), I.M. Cuper & A.V. Uhrynovskyi (2018)

When solving the problems of developing fields at the fourth stage, its residual reserves should not be completely equated with the hard-to-recover reserves of new fields with great depths and complex geological structure. The reserves of late-stage oil deposits can be considered extremely hard to recover in terms of their qualitative characteristics and their architecture is partly a consequence of previous technological actions, the imperfection of the development system, waterflooding system, well tapping and development methods, and operating modes.

The hard-to-recover reserves (Fig. 2) include reserves that are not fully recoverable due to: low water displacement capacity; unevenness of the displacement front; heterogeneity of the structure and reservoir properties of the pore space; clogging of pore channels and their compression; presence of low-permeability layers not covered by waterflooding; high rates of extraction from high-permeability layers; location of oil residues in the inter-well areas in conditions of insufficient well grid density and

formation of interference zones; accumulation of oil in peripheral undrilled areas with a small oil-saturated thickness, in low-permeability surface or bottom areas, in thin-layer oil rims. These reasons are also mentioned in V.O. Fedorishyn (2005), M.I. Yurkiv (2008) and A.Y. Dandekar (2013).

The late stage of field development is also characterised by the fact that oil production revenues are insufficient to maintain industrial communications and field infrastructure in a functional state, as already noted by such scholars as D.O. Yeher *et al.* (2005), Ya. Vytvytskyi (2008) and I.M. Ivanchenko (2011). This requires a critical review of both technological and economic approaches to facilitate the cost-effective recovery of remaining oil reserves and achieve the design oil recovery factor. In the technological aspect, the efforts of the subsoil user at the late stage of development are aimed at increasing the rate and completeness of the production of residual reserves, the structure of which, according to average data, is shown in Figure 3.

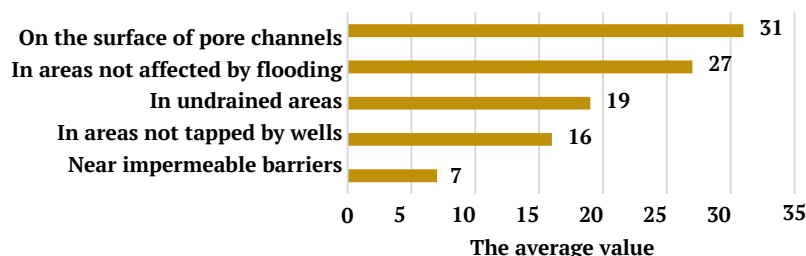


Figure 3. Residual oil location in the pore space

Source: created by the authors based on T.D. Van Golf-Racht (1982), V.O. Fedorishyn (2005), V.P. Gryshanenko *et al.* (2015)

The authors formulated and grouped the main groups of features that determine the state of the late stage of

development as geological and industrial, socio-economic and environmental (Fig. 4).

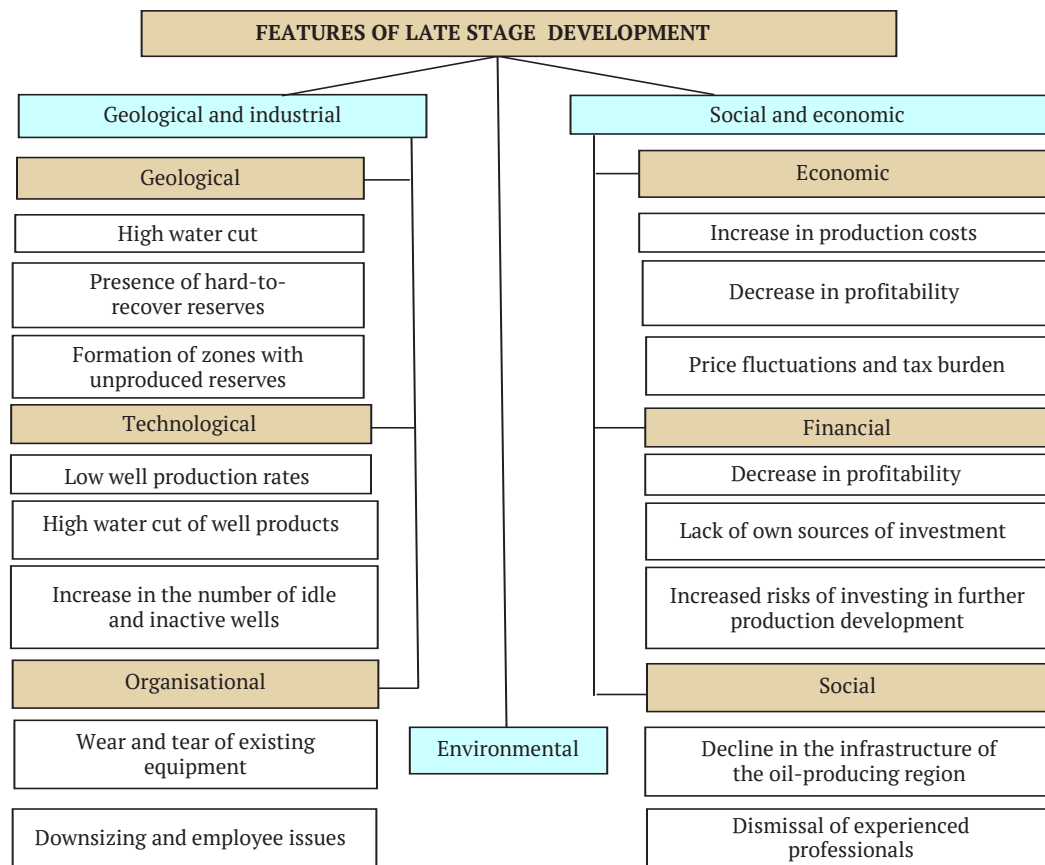


Figure 4. The main groups of features of the late stage of oil field development

Source: created by the authors

Taken together, these features are decisive in the formation of objects and directions of investment activity of enterprises that operate deposits at a late stage of their development, but the leading one is the geological and industrial group, the state and development of which determines the form and content of social and economic activities. Environmental factors are also important, caused primarily by physical "aging" of underground and surface equipment and loss of its integrity, formation of springs, increased level of environmental pollution, and environmental degradation, as is the case in the fields of Western Ukraine and Poland, as described in Oil and Gas Institute (2004) and I.M. Ivanchenko (2011). One of the main problems of late-stage oil field development, which is the case for the majority of fields on the European, American and East Asian continents, is the identification of the defining features of the stage in order to develop technical and economic measures to stabilise and increase oil production.

Summarising the geological and filtration-capacitive characteristics of oil field reservoirs, physical and chemical properties of fluids and thermobaric conditions that accompany late-stage development processes, the authors, as well as partially V.P. Gryshanenko *et al.* (2015), identified the following. The deployment of targeted industrial and scientific research is aimed at determining the location and assessing the volume and structure of residual oil in the subsoil. It is necessary to create geological, technical and

filtration-capacitive models of oil-saturated objects, while distinguishing different types of residual reserves. A systematic approach to organising the impact on the bottom-hole zone, filter and wellbore is aimed at integrating these elements into a single hydrodynamic well formation system to increase well productivity and reduce water cut of the produced product. The optimisation of waterflooding systems should include adjusting the operating modes of injection wells and coordinating their operation with production wells. The use of flow deflecting technologies can improve the efficiency of hydrocarbon production processes. Polymer flooding is required to seal wells of complex architecture, including multilateral wells with horizontal boreholes and productive reservoir opening in depression or equilibrium mode, and is an important step in the process of efficient production. It is necessary to refuse abandonment of wells if their technical condition is acceptable, and to consider the possibility of using them in intermittent operation or as injection or observation wells.

In this direction, with the participation of the authors V.P. Gryshanenko *et al.* (2015), the principles and technologies of systematic targeted isolating and stimulating effects on the bottomhole zone, filter, wellbore, pay zone and interwell zones of the reservoir have already been developed. A number of methods and technologies have been elaborated to develop oil reservoirs, limit the inflow of formation water and eliminate leakage in the wellbore space

of injection and production wells, as well as modern approaches to reinterpreting the results of seismic and geophysical surveys of wells and building permanent hydrodynamic models of hydrocarbon deposits (Boyko *et al.*, 1996; Oil and Gas Institute, 2004; Gryshchenko *et al.*, 2015).

A.A. Isaev *et al.* (2022) also noted that intensification of residue recovery from fields at a late stage of development is one of the most difficult and at the same time urgent tasks for the industry. In particular, the authors noted a possible increase in water cut at the third and fourth stages of development. Intensification of hydrocarbon inflow into a well was also considered by Y.D. Kachmar *et al.* (2004). The implementation of organisational tasks in the current study is to develop appropriate industry programmes and regulations to streamline production activities at the late stage of field development. There is a need for a mandatory recalculation of oil reserves and preparation of projects for the completion of fields, enhanced control and regulation of relations between the state and subsoil users, ensuring conditions for attracting investments and reducing the risks of implementing programmes to improve field development systems and implementing measures to increase oil recovery. When addressing social issues, it is necessary to take into account the presence of developed infrastructure at the fields, highly qualified production and technical personnel, whose downsizing should be carried out mainly on the basis of age and disciplinary principles, possible deterioration of the environmental balance and strengthening of the relevant permanent control.

Financial and economic problems are subject to the principles of increasing technical and technological risks against the background of rising production costs, decreasing cash flows, lower profitability and reduced opportunities for own investments. This was also noted by D.O. Yeher *et al.* (2005), Ya. Vytvytskyi (2008) and I.M. Petrenko *et al.* (2021), which confirms this opinion. Government support for preferential taxation of oil production from fields at a late stage of development is also important here, as it has been introduced, for example, in the United States and Canada. Thus, as noted earlier, these studies did not take into account or only partially take into account ways to solve the problem of increasing oil production at the later stages of field development. Not all of them consider economic factors, in particular. In this study, a comprehensive systematisation of the features of late-stage oil field development was carried out, and appropriate recommendations were provided that will not only temporarily increase productivity but also provide long-term benefits.

Conclusions

One of the most important tasks was to determine the criteria for identifying the presence and structure of residual

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undeveloped oil reserves in the reservoir pore space. The main problems of the late stage of field development are summarised. In this aspect, the factors that cause low oil recovery factors were considered, including the difficulty of recovering residual reserves due to the low water displacement capacity, the actual filtration and capacitive heterogeneity of the pore space structure, and the low water displacement capacity in the reservoir pressure maintenance system, clogging of the pore space with mechanical particles and asphalt-paraffin deposits with the formation of low-permeability layers, and a package of unique and targeted methods of impacting the reservoir system (flow-diverting technologies, levelling of the injection profile, compaction drilling, isolation of aquifers and intensification of oil-saturated ones). The features of the late stage of oil field development were categorised into geological, technological, economic, social and environmental. Typical directions of technical and economic measures to stabilise and increase oil and gas production at the late stage of field development were formulated. Using the graph-analytical method, the authors proposed to determine the beginning of the late stage of field development based on the analysis of curves of accumulated oil production and water cut, which gives grounds for starting active investment in technical and technological processes of oil production. The "old" oil producing regions have significant potential for increasing recoverable reserves, both through additional exploration and improvement of field development systems.

This paper is a comprehensive study that not only analysed current issues and formulated the defining features of the late stage of oil field development, but also provided recommendations for further theoretical and applied research in the field of oil and gas production aimed at improving the supply of hydrocarbons to Ukraine and increasing the efficiency and profitability of hydrocarbon production. A thorough review and comprehensive grouping of the main factors was carried out and their architecture was built to select and justify effective measures to recover residual oil reserves, maintain production profitability and ensure environmental sustainability. The directions for further theoretical and applied research are: improvement and development of new methods and technologies for impacting the formation and bottomhole zone, optimisation of waterflooding systems to recover undrained residual reserves and increase oil production at the late stage of field development.

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Conflict of Interest

None.

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Особливості розробки нафтових родовищ України на пізній стадії та напрямки нарощування видобутку нафти

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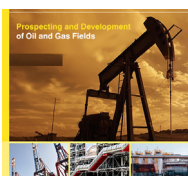
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Анотація. Актуальність роботи полягає в ідентифікації типових стадій розробки нафтових родовищ та визначенні початку настання періоду пізньої стадії на підставі фактичних значень річного та накопиченого видобутку нафти й обводненості продукції свердловин. Метою роботи було визначення головних ознак пізньої стадії розробки та напрацювання техніко-економічних напрямків і заходів щодо стабілізації та нарощування видобутку нафти й газу. Здійснено аналіз можливостей нарощування власного видобутку нафти в Україні з використання ресурсного потенціалу родовищ, запаси яких відносяться до категорії важковидобувних. Сформульовано критерії, за якими окремі поклади й родовища містять важковидобувні запаси, та встановлено структуру таких запасів з урахуванням елементів залишкової нафтонасиченості порового простору. Установлено особливості розробки родовищ на пізній стадії у частині динаміки зміни показників розробки. Розглянуто геолого-промислові, економічні, соціальні та екологічні проблеми, що супроводжують розробку родовищ на пізній стадії. На прикладі розвитку нафтовидобувної галузі України виконано аналіз типових стадій освоєння родовищ та видобування нафти й газу. Представлено структуру запасів нафти, класифікованих на активні, що вилучаються здебільшого за рахунок природної пластової енергії, та важковидобувні, які вимагають застосування спрямованої штучної дії на пластову систему з використанням різноманітних адресних методів і технологій. Запропоновано й показано на реальних фактичних даних процедуру визначення початку пізньої стадії розробки родовищ за кривими фактичного накопиченого видобутку нафти та обводненості продукції свердловин. Ідентифіковано локацію залишкових важковидобувних запасів у нафтонасиченому поровому просторі. За наявною середньостатистичною інформацією всебічно розкрито визначальні ознаки пізньої стадії розробки, які угруповано на геологічні, технологічні, організаційні, економічні, фінансові, соціальні та екологічні. Визначено головні напрямки дії науково-дослідних і нафтогазовидобувних компаній на вирішення проблеми стабілізації та нарощування видобутку нафти на пізніх стадіях розробки родовищ

Ключові слова: нафтові родовища; показники розробки; важковидобувні запаси; залишкова нафта; нафтовилучення; збільшення видобутку



Application of Hofer's formula in thermal hydraulic calculations of oil transportation systems

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Abstract. Hydrodynamic calculations are a mandatory procedure when designing new and upgrading and operating existing oil transportation systems, which are performed using computer methods. The implementation of new calculation technologies creates conditions for the use of more accurate mathematical models to describe the hydrodynamic processes that accompany the movement of liquid hydrocarbons in a pipeline. For this purpose, based on theoretical studies and mathematical modelling, the article proposed an improved method of thermal-hydraulic calculation of a pipeline for pumping oil and oil products, which takes into account the non-isothermal regime caused by the difference between the product temperature at the beginning of the pipeline and the ground temperature and the release of frictional heat of the flow. The method is based on the application of the universal Hofer's formula for determining the hydraulic drag coefficient in three friction zones of the turbulent regime, involves finding the variable regime coefficients in the Leibenson mathematical model in each section of the pipeline, and applies an integral method for calculating thermal and hydraulic energy losses during the transportation of oil and oil products. The method is suitable for creating computational algorithms and computer programs for design and operational calculations of oil and oil products transportation by pipelines without preheating the products and in the case of using special technologies that involve their preheating. The method was tested by performing multivariate calculations and analysing the results. The analytical dependences of the Leibenson's model mode coefficients on the Reynolds number and relative surface roughness of the pipe were obtained, which can be used in the thermal-hydraulic calculations of pipelines of all standard diameters at different values of surface roughness

Keywords: oil pipeline; oil product pipeline; hydraulic resistance coefficient; Leibenson's formula; pressure loss due to friction; non-isothermal flow; flow friction heat

Introduction

The issues of high-quality design and energy-efficient operation of main pipelines and oil product pipelines play an important role in ensuring the energy security of any country, including Ukraine. In the design and operation of main pipelines for the transportation of oil and oil products, i.e. liquid hydrocarbons, one of the main computational

operations is hydraulic calculation. The results of hydraulic calculations are used to select pumping equipment for pumping stations, determine the throughput capacity and energy efficiency of the pipeline. A number of works by both Ukrainian and foreign scientists have been devoted to the methods of hydraulic calculation of pipelines. All of them

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use the Darcy-Weisbach equation to calculate pressure losses from friction. Differences in approaches lie in different methods of determining the hydraulic resistance coefficient and different ways of taking into account the physical properties of the medium transported by the pipeline.

In most cases, the existing methods of hydraulic calculation of main pipelines, in the absence of special technologies, do not take into account the processes of heat generation during the movement of fluid and its exchange with the environment in the pipeline-soil system, assuming the operation of such oil transportation systems to be isothermal. In real pipelines, the conditions of isothermal hydrocarbon transportation are rarely met. The product that is pumped into the pipeline usually has a temperature that differs from the ground temperature at the depth of the pipe. In addition, the movement of a real fluid, characterised by viscosity, is accompanied by the generation of frictional heat, which changes the operating temperature and, consequently, the pressure loss from friction in the pipeline. The effect of non-isothermicity is much greater in "hot pipelines", which use a special technology for pumping heated high-viscosity hydrocarbons. The hydraulic calculation of such pipelines also needs to take into account the frictional heat of the flow. This factor of influence on the operating parameters of the oil transportation system is often neglected, as noted by H. Li *et al.* (2024). Non-isothermal pumping is characterised by a change in the thermophysical properties of the transported product due to temperature changes along the pipeline. This temperature change can be described by the heat balance equation, which must take into account the internal frictional heat of the flow. This opinion is shared by a number of authors of other scientific papers, such as U.K. Zhabbasbayev *et al.* (2021) and E. Liu *et al.* (2022).

The current Ukrainian standards for the technological design of main oil pipelines recommend a method of hydraulic calculation of the pipeline based on the steady-state isothermal operation of the pipeline, where the temperature, density, volume flow rate and viscosity of the transported product are constant along the length. Regulatory documents and existing methodologies offer dozens of formulas for the hydraulic resistance coefficient, depending on the mode of product movement - laminar, transient or turbulent. The current standards for the technological design of oil pipelines provide for the use of four formulas for the hydraulic drag coefficient, which do not fit well with the recommended Reynolds limit numbers (DNTD 2-86, 1986).

The formulas for the Reynolds limit numbers proposed by different authors give fundamentally different results. All this makes it difficult to create computational algorithms and computer programmes to determine the capacity and energy efficiency of oil and oil product pipelines. In the world practice, hydraulic calculations of pipelines are based on universal mathematical models that provide reliable results for determining the hydraulic drag coefficient for all three zones of the turbulent regime. An analysis of numerous publications by scientists has shown a

unanimous opinion that the Colebrook and White formula provides the greatest accuracy in determining the hydraulic drag coefficient. Since this formula does not give an explicit solution, scientists, in particular F.L. Kaseng *et al.* (2020), S.L. Tolentino & O.G. Campos (2023) and M. López-Silva *et al.* (2024), have been working on methods to create reliable approximations of it for a long time. The approximation formulas proposed by scientists have different complexity of expressions and provide unequal compliance with the basic formula of Colebrook and White. P. Benner *et al.* (2018) and C. Allen *et al.* (2021) noted that for Reynolds numbers and relative roughness values that correspond to the conditions of pipeline hydrocarbon transport, the most successful approximation of the universal Colebrook and White formula is the Hofer's formula. C.-A. Safta *et al.* (2021) confirmed the exceptional impact of pressure losses on the efficiency of hydropower systems. They investigated the scope of application of various formulas for the hydraulic resistance coefficient, including the Stokes, Blasius, and Colebrook-White formulas for determining pressure losses from friction in pipelines operating at Reynolds numbers up to $Re = 6,000$. In Ukrainian practice, the universal Colebrook and White formula and its successful approximations are practically not used. As an exception, the work of M.D. Serediuk & N.V. Motruk (2024) should be noted, which proved the feasibility of using the Hofer's formula in hydraulic calculations of high, medium and low-pressure gas networks.

Thus, despite a significant number of publications, the issues of a reasonable choice of mathematical models for the hydraulic resistance coefficient, taking into account the effect of flow friction heat on the thermal and hydraulic parameters of main oil and oil product pipelines have not been fully clarified and require additional research. The proposed study is devoted to improving the methods of design and operational calculations of pipelines for the transportation of oil and its products using traditional and special technologies. The aim of the study was to develop a method for the hydraulic calculation of a pipeline for the transportation of liquid hydrocarbons (oil and oil products), based on the application of the universal Hofer's formula for the hydraulic resistance coefficient and taking into account the non-isothermal factor caused by the difference between the initial temperature of the product and the ground temperature and the generation of frictional heat in the flow. The research objective was achieved through the following tasks:

- ◆ development of a universal method for hydraulic calculation of the pipeline, which can be used both for traditional transportation technology without heating and for special technology of pumping preheated liquid hydrocarbons;
- ◆ implementation of the proposed method in a computer programme;
- ◆ based on the results of hydrodynamic calculations, obtaining analytical expressions for the mode coefficients in the generalised Leibenzon's formula using the universal Hofer's formula for the hydraulic resistance coefficient.

Materials and Methods

When developing the pipeline hydraulic calculation method, it was assumed that hydrocarbons are pumped in a temperature range that ensures their Newtonian properties with sufficient accuracy for practical calculations. The first block of the method involved determining the total heat transfer coefficient from the product to the environment. The value of the total heat transfer coefficient K for underground pipeline installation mainly depends on the external heat transfer coefficient. In turn, the value of this coefficient is largely determined by the value of the soil thermal conductivity coefficient, which varies seasonally. The internal coefficient of heat transfer from the product to the inner surface of the pipe was calculated using the criterion equations of Reynolds, Nusselt, Prandtl and Grashof, depending on the mode of product movement in the pipeline. The following mathematical models were used to reduce the physical properties of the transported product to the calculated temperature t , °C. For density, kg/m³:

$$\rho = \rho_{20} - \xi(t - 20), \quad (1)$$

where ρ_{20} is density of the product at a temperature of 20 °C; ξ – is a temperature correction. For kinematic viscosity, m²/s:

$$\nu = a_1 + a_2 \times t + a_3 \times t^2 + a_4 \times t^3, \quad (2)$$

where a_1, a_2, a_3, a_4 are the coefficients of the mathematical model of the product's kinematic viscosity dependence on temperature. For heat capacity, J/(kg·°C):

$$c = \frac{31.56}{\sqrt{\rho_{20}}} (1,687 + 3.39 \times t). \quad (3)$$

For thermal conductivity coefficient, W/(m·°C):

$$\lambda_{hr} = \frac{137}{\rho_{20}} (1 - 0.00054 \times t). \quad (4)$$

The developed algorithm provides for the implementation of the method of successive approximations by the average flow temperature of the transported product and the average temperature of the pipe wall when determining the internal heat transfer coefficient. To take into account the effect of non-isothermicity caused by both the difference between the initial temperature of the transported product and the ground temperature as well as the influence of frictional heat of the flow, it is necessary to perform joint thermal and hydraulic calculations of the pipeline. The heat balance equation, which takes into account the frictional heat of the flow, for a pipeline section of length x , is presented in the form:

$$\frac{K\pi D}{\rho Q c} dx = - \frac{dt}{t - t_o - \phi \nu^m}, \quad (5)$$

where ϕ is a set of parameters, the value of which depends on the mode of product movement;

$$\phi = \beta \frac{\rho Q^{3-m} g}{K\pi D^{6-m}}; \quad (6)$$

$$\beta = \frac{2^{3-2m} A}{\pi^{2-m} g}, \quad (7)$$

D – inner diameter of the pipeline; t_o – ground temperature at the depth of pipeline laying; Q – volumetric flow rate; g – acceleration of gravity; A, m – coefficients of the fluid motion mode in the Leibenzon's mathematical model for the hydraulic resistance coefficient. In hydraulic calculations of pipelines for the transportation of oil and oil products, the generalised Leibenzon's formula for the hydraulic resistance coefficient is often used:

$$\lambda = \frac{A}{Re^m}, \quad (8)$$

where Re – Reynolds number. This simple mathematical model is a convenient tool for solving a number of issues related to the determination of hydrodynamic parameters of complex pipelines under different modes of hydrocarbon pumping. This formula was also used in this study. Its application made it possible to take into account the frictional heat of the flow when calculating the hydraulic resistance coefficient using the Hofer's formula:

$$\lambda = \frac{1}{\left\{ 2lg \left[\frac{4.518}{Re} lg \left(\frac{Re}{7} \right) + \frac{k_e}{3.71D} \right] \right\}^2}, \quad (9)$$

where k_e – is the absolute equivalent roughness of the pipe's inner surface. Methods of hydraulic calculation of pipelines used in practice provide for the application of specific constant values of the following coefficients, in particular $A = 0.3164$ and $m = 0.25$, which correspond to the empirical Blasius formula for the hydraulic drag coefficient in the zone of hydraulically smooth pipes in the turbulent regime. However, this formula has a limited scope in terms of the Reynolds number (DNTD 2-86, 1986). This makes it necessary to use other mathematical models for hydraulic calculations of pipelines, which include not only the Reynolds number, but also the value of pipe roughness and do not contain mode coefficients A and m .

Thus, in order to use formula (5) for the thermal calculation of the pipeline, taking into account the non-isothermal mode of product pumping, it was necessary to develop a method for finding the values of the mode coefficients A and m in the case of using other, universal formulas for the hydraulic resistance coefficient. The proposed method involves the use of the Hofer's formula (9) for all three friction zones of the turbulent regime. Unlike existing methods of hydraulic calculation of pipelines, when taking into account the non-isothermicity factor, the coefficients of the motion mode A and m were taken as variable values rather than constant ones. To obtain the corresponding dependences, formula (8) was differentiated by the Reynolds number and the differential $\frac{d\lambda}{dRe}$ from the Hofer's formula (9) was substituted into the obtained expression. As a result, the following formula for the mode coefficient is obtained (Serediuk & Motruk, 2024):

$$m = \frac{7.849 \left[lg \left(\frac{Re}{7} \right) - 0.4343 \right] \sqrt{\lambda}}{\left[4.518 lg \left(\frac{Re}{7} \right) + Re \frac{k_e}{3.71D} \right]}. \quad (10)$$

The value of the mode coefficient A for this method was found as follows:

$$A = \lambda \times Re^m. \quad (11)$$

As shown by formulas (10) and (11), the variable values of the transported product flow regime coefficients A and m depend on the Reynolds number and the roughness of the pipeline's internal surface. Generally speaking, in a non-isothermal pipeline, in certain sections of it, in addition to the turbulent pumping mode, a laminar or transient mode may occur. The following approach is proposed for determining the coefficients of the flow regime under these conditions. For the laminar regime, provided that $Re < Re_{kr} = 2,041$:

$$m = 1, A = 64; \quad (12)$$

for the transitional regime when applying the formula recommended by the current regulatory document (DNTD 2-86, 1986):

$$\lambda = (0.16 Re - 13) \times 10^{-4}; \quad (13)$$

for $Re_{kr} < Re < Re_{per}$ the following expression is obtained:

$$m = -1.6 \times 10^{-5} \frac{Re}{\lambda}, \quad (14)$$

where Re_{per} – is the transient Reynolds number that separates the transient and turbulent modes of product flow in the pipeline. The transient Reynolds number divides the scope of formula (13) and Hofer's formula (9), providing the same calculation results when they are combined. This is important when implementing the method of successive approximations when calculating the operating parameters of pipelines. Similarly, the proposed value of the critical Reynolds number $Re_{kr} = 2,041$ provides an accurate matching of the Stokes formula and formula (13) at the boundary of laminar and transient pumping modes. The value of the transient Reynolds number depends on the value of the relative roughness of the pipe. M.D. Serediuk & N.V. Motruk (2024) obtained the following formula, which describes the above dependence with an approximation reliability of more than 99% for the entire possible range of relative roughness of standard diameter pipes:

$$Re_{per} = 2,836 + 5,036 \times \varepsilon, \quad (15)$$

where $\varepsilon = \frac{k_e}{D}$ – is the relative roughness of the pipe surface. The above method made it possible to use the following calculation formula for the thermal regime of a non-isothermal pipeline (Serediuk & Pylypiv, 2013):

$$\frac{K\pi DL}{\rho_{ave} Q C_{ave}} = \int_{t_k}^{t_p} \frac{dt}{t - t_o - \phi v^m}, \quad (16)$$

where L – pipeline length; t_p, t_k – product temperature at the beginning and end of the pipeline; ave – is an index indicating the average value of the parameter along the pipeline. Equation (16) was solved with respect to the final product temperature t_k . The computational algorithm involved the use of the method of successive

approximations and the numerical method of integrating the right-hand side of equation (16). Formula (16) is written in the following form:

$$Shu = I_t, \quad (17)$$

where $Shu = \frac{K\pi DL}{\rho_{ave} Q C_{ave}}$ Shukhov's parameter. For each value of the product temperature t corresponding to a certain cross-section x of the pipeline, the following operations were performed. The local value of the Reynolds number Re in an arbitrary cross-section of a non-isothermal pipeline was determined. The corresponding values of the coefficients of the mode of motion and the values of the complexes of parameters β and ϕ associated with the consideration of the influence of frictional heat of the flow, were calculated. Using the Simpson method, the value of the determined integral I_t at which the value of the final temperature t_k is equal to the Shukhov parameter was numerically determined. After completing the thermal calculation of the pipeline, hydrodynamic calculations were performed. For a non-isothermal pipeline, the expression for the elementary friction head loss over a section of length using the generalised Leibenson mathematical model for the hydraulic drag coefficient is as follows:

$$dh_\tau = \frac{\beta v^m Q^{2-m} dx}{D^{5-m}}. \quad (18)$$

According to the heat balance equation, which takes into account the effect of flow friction, the relationship between the values dx and dt is as follows:

$$dx = \frac{l}{Shu} \times \frac{dt}{t - t_o - \phi v^m}. \quad (19)$$

Taking into account formulas (18) and (19), the equation for the head loss due to friction in a non-isothermal pipeline is written as:

$$h_\tau = \frac{L}{Shu} \int_{t_k}^{t_p} \frac{\beta v^m Q^{2-m} dt}{D^{5-m}(t - t_o - \phi v^m)}, \quad (20)$$

or

$$h_\tau = \frac{L}{I_t} I_h. \quad (21)$$

Using the Simpson method described above, the following integral was calculated numerically I_h , the value of which is proportional to the pressure loss from friction in a non-isothermal pipeline. Based on the above algorithm, a computer program was developed that makes it possible to calculate the final temperature and pressure losses for the non-isothermal technology of pipeline transport of liquid hydrocarbons. In order to test the proposed methodology, multivariate thermal-hydraulic calculations were performed with the following data: length of the pipeline section between oil pumping stations $L = 120$ km; outer diameter of the pipeline $D_3 = 0.530$ m; inner diameter of the pipeline $D = 0.514$ m; no thermal insulation; depth of the pipeline axis $h_o = 1.5$ m; oil temperature at the beginning of the pipeline $t_p = 10$ °C; ground temperature at the depth of pipeline laying $t_o = 1$ °C; thermal conductivity of the ground $\lambda_{hr} = 1.0$ W/(m·°C); thermal conductivity of the pipe metal

$\lambda_c = 58 \text{ W/(m} \cdot \text{°C)}$. Coefficients of the mathematical model of oil viscometricity: $a_1 = 77.6 \times 10^{-6}$; $a_2 = -8.041 \times 10^{-6}$; $a_3 = 0.3674 \times 10^{-6}$; $a_4 = -5.582 \times 10^{-9}$. Oil density at temperature 20 °C $\rho_{20} = 867 \text{ kg/m}^3$. Absolute equivalent roughness of the inner surface of the pipe $k_e = 1 \times 10^{-4} \text{ m}$.

Results and Discussion

The results of thermal and hydraulic calculations based on the developed and existing methods were performed for different degrees of oil pipeline loading and are summarised in Table 1.

Table 1. Results of oil pipeline calculation taking into account frictional heat of oil flow

Parameter	Parameter value at oil consumption, m ³ /h			
	500	700	900	1,100
Shukhov parameter	1.3289	0.9572	0.7459	0.6111
Oil temperature at the end of the pipeline, °C	4.0	5.6	7.1	8.5
Total heat transfer coefficient from oil to the environment, W/(m ² ·°C)	1.53	1.54	1.54	1.54
Frictional pressure loss according to the developed method, MPa	1.49	2.61	3.97	5.57
Pressure loss from friction by the method of isothermal pumping, MPa	1.74	3.13	4.86	6.90
The degree of refinement of energy consumption of oil transportation, %	-14.2	-16.6	-18.2	-19.3

Note: initial oil temperature is 10°C

Source: developed by the authors

As can be seen from Table 1, taking into account the non-isothermal factor when transporting medium-viscosity oil through a pipeline makes it possible to significantly refine its hydrodynamic energy consumption. Table 2

contains the results of the thermal-hydraulic calculation of the pipeline, the parameters of which are indicated above, when pumping oil with the same physical properties as in the previous case, but heated to a temperature of 30°C.

Table 2. Results of oil pipeline calculation taking into account frictional heat of oil flow

Parameter	Parameter value for oil consumption, m ³ /h			
	500	700	900	1,100
Shukhov parameter	1.3289	0.9517	0.7413	0.6071
Oil temperature at the end of the pipeline, °C	1.54	1.54	1.55	1.55
Total heat transfer coefficient from oil to the environment, W/(m ² ·°C)	9.18	13.10	16.42	19.10
Frictional pressure loss according to the developed method, MPa	1.27	2.25	3.49	4.99
Pressure loss from friction by the method of isothermal pumping, MPa	1.74	3.13	4.86	6.90
The degree of refinement of energy consumption of oil transportation, %	-27.0	-28.2	-28.1	-27.7

Note: initial oil temperature is 30°C

Source: developed by the authors

As noted above, in the case of applying the proposed method of thermal-hydraulic calculation of the pipeline, the mode coefficients are variable parameters, functions of the Reynolds number and relative roughness of the pipe surface. To establish the form of these functions, the developed program performed multivariate calculations and found the values of the mode coefficients for the

entire range of possible loading of the oil pipeline, the parameters of which are given above. Based on the results of the calculations, graphical dependences of the values of the mode coefficients m and A and the Reynolds number were constructed. They were mathematically modelled using the Excel spreadsheet processor. The results are illustrated in Figure 1.

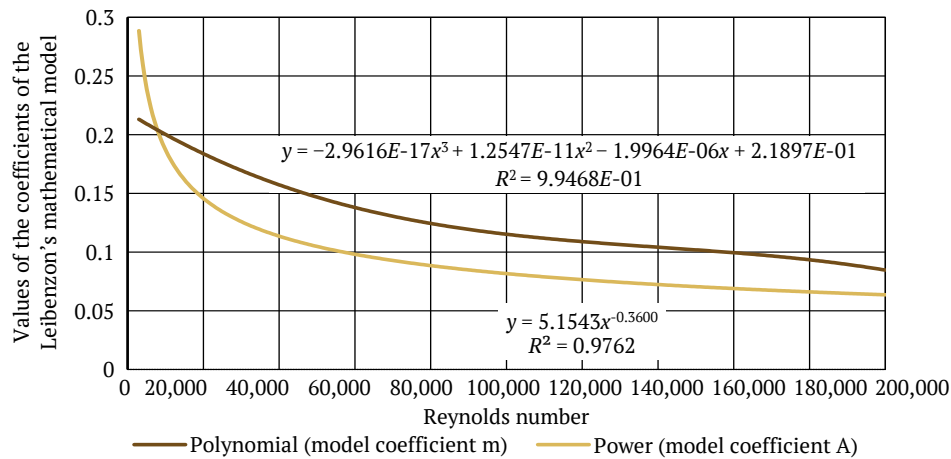


Figure 1. Dependence of the coefficients of the motion mode in the Leibenzon's formula on the Reynolds number for a pipeline with a diameter of 0.514 m and an absolute roughness of 1×10^{-4} m

Source: developed by the authors

In order to transfer the results obtained to pipelines of other diameters with different surface roughness, the Hofer's formula was written in terms of the relative roughness of the pipe ε . The possible range of changes in the diameters of main pipelines and their surface roughness were determined. The absolute equivalent roughness of real pipelines varies from 1×10^{-4} m to 2×10^{-4} m. The standard diameters of pipelines for pumping liquid hydrocarbons vary from DN 100 to DN 1,200. Based on the results of multivariate thermal-hydraulic calculations and their mathematical modelling using the Excel spreadsheet processor, the following generalised dependencies of the flow mode coefficients on the Reynolds number and relative roughness are obtained, which are valid for a pipeline of any diameter. For the coefficient m :

$$m = b_1 + b_2 \times Re + b_3 \times Re^2 + b_4 \times Re^3, \quad (22)$$

where b_1, b_2, b_3, b_4 are the coefficients of the mathematical model, the values of which depend on the relative roughness of the pipe surface:

$$b_1 = 0.2102 \times \varepsilon^{-0.0048}; \quad (23)$$

$$b_2 = -1.9048 \times 10^{-6} - 4.8951 \times 10^{-4} \times \varepsilon + 2.4069 \times 10^{-1} \times \varepsilon^2; \quad (24)$$

$$b_3 = 1.1792 \times 10^{-11} + 4.0277 \times 10^{-9} \times \varepsilon - 2.0944 \times 10^{-6} \times \varepsilon^2; \quad (25)$$

$$b_4 = -2.7258 \times 10^{-17} - 1.4580 \times 10^{-14} \times \varepsilon + 1.5646 \times 10^{-11} \times \varepsilon^2 - 6.3197 \times 10^{-9} \times \varepsilon^3; \quad (26)$$

for the coefficient A :

$$A = K_a \times Re^\chi, \quad (27)$$

where K_a, χ – are the coefficients of the mathematical model, the values of which depend on the relative roughness of the pipe surface:

$$K_a = 13.764 - 1.5363 \times 10^4 \times \varepsilon + 7.4986 \times 10^6 \times \varepsilon^2; \quad (28)$$

$$\chi = -0.47346 + 166.10 \times \varepsilon - 57,913 \times \varepsilon^2. \quad (29)$$

The reliability of the approximation of formulas (22-29) exceeds 98%. The proposed methodology, with the reasonable use of the Hofer's formula to determine the hydraulic resistance coefficient of the system and taking into account the non-isothermal flow of the medium transported by main pipelines, as well as the obtained analytical dependences of the mode coefficients included in the generalised Leibenzon formula, can be used with a sufficiently high accuracy of the results obtained in the development of computational algorithms for thermal and hydraulic calculations of pipelines of complex configuration, which implement various modes of liquid hydrocarbon pumping with appropriate rheological characteristics.

Progressive technologies for the production and use of alternative gaseous energy carriers, including gas-hydrogen mixtures, hydrogen, biomethane, etc., are being intensively introduced. Despite this, the scope and volume of use of liquid hydrocarbons – oil and oil products – is not decreasing. Pipeline transport plays a crucial role in transporting large volumes of liquid hydrocarbons over long distances. Pipeline transportation of hydrocarbon energy carriers, in particular oil and oil products, is an influential strategic factor in the country's economic stability and energy security, provided that it is operated reliably and safely. In the global practice of hydraulic calculations, different formulas are used for the hydraulic resistance coefficient, taking into account the purpose and geometric characteristics of the pipeline, physical properties of the transported product and pumping volumes.

For example, T. Bekibayev *et al.* (2021) presented the results of studies on the identification of the hydraulic resistance coefficient in main oil pipelines. The authors consider the process of non-isothermal oil pumping,

taking into account heat exchange with the environment. The change in oil viscosity along the length of the pipeline, as well as the change in pipe surface roughness during its operation, are taken into account. Based on the data of industrial experiments on existing oil pipelines, a formula for the hydraulic resistance coefficient is proposed for the laminar mode of pumping, which differs by a numerical coefficient from the classical Stokes formula, stating that the use of the Colebrook and White formula for the turbulent mode of oil flow causes certain difficulties in the implementation of hydraulic calculations of pipelines. Therefore, it is advisable to use reliable approximations of this formula. A modified Altschul formula is proposed for determining the hydraulic drag coefficient, which gives results that differ by several percent from the Colebrook values. It should be noted that the adequacy of the Altschul formula was verified based on the results of industrial experiments in a narrow range of Reynolds numbers $Re = (10,000 - 30,000)$. The actual range of Reynolds numbers in main oil and oil product pipelines is much larger and can be $Re = (3,000 - 200,000)$. T. Bekibayev *et al.* (2021) proposed an adjusted Stokes formula for the laminar regime, based on the results of industrial experiments at $Re < 2,100$:

$$\lambda = \frac{71.6}{Re}. \quad (30)$$

For the turbulent regime of oil pumping through a pipeline at Reynolds numbers, T. Bekibayev *et al.* (2021) confirmed the adequacy of the Altschul formula, which is an approximation of the Colebrook and White formula. N. Luta & N. Antonyuk (2024) recommended using a complex approximation of the Zigrang and Sylvester equation in the turbulent mode of pumping light oil products:

$$\frac{1}{2\sqrt{\lambda}} = -2 \lg \left\{ \frac{k_e}{3.7D} - \frac{5.02}{Re} \lg \left[\frac{k_e}{3.7D} - \frac{5.02}{Re} \lg \left(\frac{k_e}{3.7D} + \frac{13}{Re} \right) \right] \right\}. \quad (31)$$

M.D. Serediuk & N.V. Motruk (2024) proved the feasibility of using the Hofer's formula for the hydraulic resistance coefficient in the hydraulic calculation of gas distribution networks of all categories of working pressure. A.O. Gallardo *et al.* (2021), Z. Hafsi (2021) and H.M. Benavides-Muñoz (2024), and many others have confirmed that the Colebrook and White formula provides the highest accuracy in determining the hydraulic drag coefficient in turbulent conditions. A.O. Gallardo *et al.* (2021) analysed the scope of application of seven explicit approximations of this formula and proposed their own version for the hydraulic calculation of pipeline water distribution systems. The works by R.T.D.A. Minihoni *et al.* (2020) and L.E. Muzzo *et al.* (2021) compared the explicit approximations of the Colebrook and White equation for determining the hydraulic resistance coefficient proposed by other authors in terms of the accuracy of the calculation results and the efficiency of application.

H.M. Benavides-Muñoz (2024) proposed two new refined modifications of the Churchill's equation to calculate the hydraulic drag coefficient. The reliability and accuracy

of the conducted studies are substantiated by comparing them with the results obtained by the Colebrook and White formula. Z. Hafsi (2021), to determine the hydraulic drag coefficient, gave a direct analytical solution to the Colebrook and White equation by decomposing a third-order polynomial using the Cardano method. F.A. Daneshvar *et al.* (2023) proposed a methodology for determining the hydraulic drag coefficient based on the numerical solution of the Colebrook and White equation in the studied range of fluid velocities, commercial diameters, and roughness parameters of GRP pipes. In X. Fang *et al.* (2020) provided an overview of existing correlation models for determining the hydraulic drag coefficient in refrigerant transport systems at supercritical pressures and propose a new friction coefficient model for turbulent flow with high prediction accuracy.

F. Fiorillo *et al.* (2024) proposed a methodology for applying Poiseuille and Darcy-Weisbach laws to describe groundwater flow under laminar and turbulent fluid motion in porous aquifers and their relationship in the transition zone between laminar and turbulent flows. I. Santos-Ruiz *et al.* (2021) proposed a fundamentally different way to improve the accuracy of pipeline hydraulic design under turbulent conditions. Using the Lambert function and nonlinear optimisation methods, the authors processed the results of experimental studies of fluid pumping modes at a pilot pipeline installation. As a result, the authors established the dependence of the hydraulic drag coefficient on the Reynolds number and pipe surface roughness.

G.B. Ferreri (2024) proposed a new approach to estimating the hydraulic drag coefficient using approximate formulas obtained by mathematically processing a large array of data created by systematically solving the Colebrook and White formula in the appropriate ranges of Reynolds numbers Re and relative roughness ε . The author has proposed two mathematical expressions for determining the hydraulic drag coefficient, which can be used in two steps to improve the accuracy of calculations:

$$\lambda' = a' \lambda_\infty, \quad (32)$$

and

$$\frac{1}{\sqrt{\lambda'}} = -2 \lg \left(\frac{2.51}{Re \sqrt{\lambda'}} + \frac{\varepsilon}{3.71D} \right), \quad (33)$$

where

$$\frac{1}{\sqrt{\lambda_\infty}} = -2 \lg \left(\frac{\varepsilon}{3.71D} \right); \quad (34)$$

$$a' = 1 + 0.006 \left(\frac{\varepsilon}{D} \right)^{-0.203} \left[\lg \left(\frac{0.860}{\left(\frac{\varepsilon}{D} \right)^{0.0985}} \right) \right]^{\lg \left(\frac{Re}{Re} \right)}; \quad (35)$$

$$Re^n \approx \frac{70\sqrt{8}}{\sqrt{\lambda_\infty \frac{\varepsilon}{D}}}. \quad (36)$$

According to the research of G.B. Ferreri (2024), the use of only formula (32) in combination with (34-36) to

calculate the hydraulic resistance coefficient allows for 93% of cases to obtain an accuracy of calculations with an error of up to 3%, the use of formula (33) additionally increases the accuracy of the results obtained with an error of up to 0.79%. P. Praks & D. Brkić (2020) proposed two explicit approximations of the Colebrook and White equation, obtained using the Lambert W-function and the Wright Omega function, with a relatively small error and short machine calculation time. In the work of D. Brkić (2024), taking into account the research presented in P.R. De Souza Mendes (2024), new approaches to solving practical problems of determining pressure losses $\rho g \Delta h$ in hydraulic systems using the classical Moody diagram, rebuilt in the coordinates of Reynolds numbers and a modified hydraulic resistance coefficient are considered:

$$\lambda^* = \frac{\rho g \Delta h D^2}{32 \mu V L}, \quad (37)$$

which for the laminar regime of fluid motion is taken equal to 1, and for the turbulent regime, according to the Colebrook and White formula, is determined by:

$$\frac{\sqrt{Re}}{\sqrt{\lambda^*}} = -16 \lg \left(\frac{0.314 \sqrt{Re}}{Re} + \frac{\varepsilon/D}{3.71} \right), \quad (38)$$

where μ , V , L – are, respectively, the dynamic viscosity coefficient, fluid velocity, and length of the hydraulic system. M. Khlapuk *et al.* (2021) used the dimensional analysis method to process the results of Nikurajze's experimental studies and proposed the following formula for the hydraulic drag coefficient in the zone of hydraulically smooth pipes in the turbulent regime:

$$\lambda = 64 \left(\frac{0.01034}{Re^{0.5}} + \frac{0.03124}{Re^{0.5}} + 0.0000726 \right). \quad (39)$$

According to M. Khlapuk *et al.* (2021), the results of the calculation using this formula are in better agreement with Nikuradse's experimental data. However, the formula works only in one friction zone of the turbulent regime. In M.M. Khlapuk *et al.* (2019), the researchers developed the theoretical foundations of fluid movement in a pipeline, proposing a solution to the following equation for the distribution of the average fluid velocity in a turbulent regime:

$$u_{xt} = \lambda Re^2 \frac{v^2}{64 v_{tot} r_o^3} (r_o^2 - r^2), \quad (40)$$

where v is the molecular kinematic viscosity of the fluid; v_{tot} is the total kinematic viscosity, which takes into account the molecular kinematic viscosity on the pipeline wall and the kinematic turbulent viscosity between the flow layers; r_o is the pipe radius; r is the arbitrary radius of the fluid flow layer. The authors of the paper proposed to use the Hofer's formula when performing thermal and hydraulic calculations of main pipelines for the transportation of liquid hydrocarbons, which, unlike the explicit approximations of

the Colebrook and White formula recommended by other authors above, allows determining the hydraulic resistance coefficient using one dependence for the entire range of turbulent fluid flow, while also ensuring accurate matching of numerical values of this variable at the transition between laminar and turbulent modes. The application of the Hofer's formula made it possible to develop a methodology for calculating the thermal and hydraulic parameters of main oil and oil product pipelines, taking into account the factors of non-isothermal flow, which in most cases are not taken into account when transporting liquids characterised by Newtonian properties. The method proposed by the authors was tested on the basis of multivariate calculations and analysis of the results obtained.

Conclusions

A method and software for the thermal and hydraulic calculation of a pipeline with regard to the non-isothermal mode of oil and oil products transportation has been developed. The method is applicable to any product flow regimes in the pipeline, including laminar, transient and all three turbulent zones. It involves the application of the generalised Hofer's formula to determine the hydraulic drag coefficient for all friction zones of the turbulent regime and takes into account the impact of flow friction heat on the energy consumption of product transportation.

The introduction of variable mode coefficients in the generalised Leibenzon's model for the hydraulic resistance coefficient makes it possible to unify the method of thermal and hydraulic calculation of pipelines in a wide range of Reynolds numbers and values of pipe surface roughness. It has been found that in the case of applying the Hofer's formula to calculate the hydraulic resistance coefficient in pipelines of any diameter, the dependence of the mode coefficients in the Leibenzon's mathematical model on the Reynolds number and relative roughness with an approximation reliability of more than 98% can be described by polynomials of the second and third order, as well as by the power function.

It has been established that taking into account the non-isothermicity caused by the difference between the initial oil temperature and the ground temperature, and the generation of frictional heat in the flow allows to specify hydrodynamic pressure losses by 14-19% depending on the degree of pipeline loading. The proposed methodology and the established models for the mode coefficients can be used in further studies related to the operation of pipelines of complex configuration, which implement various technologies and modes of pumping liquid hydrocarbons characterised by both Newtonian and anomalous rheological properties.

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None.

Conflict of Interest

None.

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Застосування формули Хофера при теплогідравлічних розрахунках нафтотранспортних систем

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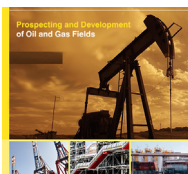
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Анотація. Під час проєктування нових і модернізації та експлуатації існуючих нафтотранспортних систем обов'язковою процедурою є гідродинамічні розрахунки, які виконують зі застосуванням комп'ютерних методів. Реалізація нових технологій розрахунку створює умови для використання більш точних математичних моделей для опису гідродинамічних процесів, що супроводжують рух рідких вуглеводнів у трубопроводі. З цією метою, на основі теоретичних досліджень та математичного моделювання, у статті запропоновано удосконалений метод теплогідравлічного розрахунку трубопроводу для перекачування нафти та нафтопродуктів, який враховує неізотермічність режиму, спричинену відмінністю температури продукту на початку трубопроводу від температури ґрунту та виділенням тепла тертя потоку. Метод базується на застосуванні універсальної формули Хофера для визначення коефіцієнта гідравлічного опору в умовах трьох зон тертя турбулентного режиму, передбачає знаходження змінних коефіцієнтів режиму в математичній моделі Лейбензона в кожному перерізі трубопроводу, застосовує інтегральний спосіб обчислення теплових та гідравлічних втрат енергії під час транспортування нафти і нафтопродуктів. Метод придатний для створення обчислювальних алгоритмів та комп'ютерних програм проєктних та експлуатаційних розрахунків транспортування нафти і нафтопродуктів трубопроводами без підігріву продуктів та у разі застосування спеціальних технологій, що передбачають їх попередній підігрів. Виконано апробацію методу шляхом проведення багатоваріантних розрахунків та аналізу отриманих результатів. Одержано аналітичні залежності величини коефіцієнтів режиму моделі Лейбензона від числа Рейнольдса та відносної шорсткості поверхні труби, які можна застосовувати в теплогідравлічних розрахунках трубопроводів усіх стандартних діаметрів за різних значень шорсткості поверхні

Ключові слова: нафтопровід; нафтопродуктопровід; коефіцієнт гідравлічного опору; формула Лейбензона; втрати тиску від тертя; неізотермічність потоку; тепло тертя потоку



Efficiency of various desulphurisation methods in improving the quality of the propane-propylene fraction

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Abstract. The study was conducted to determine the most effective and economically substantiated desulphurisation method for oil and gas deposits, ensuring a minimum content of sulphur compounds in the propane-propylene fraction. In this study, the methods of absorption, adsorption, and chemical purification, including catalytic, were compared in terms of hydrogen sulphide removal efficiency, economic feasibility, and impact on the final quality of the propane-propylene fraction. As a result of the analysis, it was found that the effectiveness of various methods of desulphurisation of the propane-propylene fraction depends on the initial concentration of hydrogen sulphide, the technical characteristics of the equipment, and the economic operating conditions. Absorption methods using amine solutions showed the highest degree of purification, reducing the hydrogen sulphide content to less than 5 ppm for large volumes of gas. However, the significant costs of absorbent regeneration reduce their economic attractiveness. Adsorption using zeolites and activated carbon has demonstrated high efficiency in processing small and medium volumes of gas. However, a reduction in the hydrogen sulphide content to 10 ppm is achieved, and adsorbent regeneration is possible without significant costs, which makes the method preferable for small installations. Catalytic purification using oxidising agents proved to be less effective at high concentrations of hydrogen sulphide, but ensures stable operation at low levels of impurities. This method requires significant capital investments, but it allows obtaining a fraction with a sulphur content of less than 8 ppm. Based on the data obtained, it was established that the choice of the optimal desulphurisation method is determined by the scale of production and the acceptable economic costs. Absorption is preferable for large enterprises, while the adsorption method is optimal for small installations

Keywords: absorption; zeolites; adsorption; activated carbon; catalytic purification

Introduction

Purification of the propane-propylene fraction from sulphur compounds is an important task to improve its quality and meet modern requirements of industrial processing and environmental standards. The presence of hydrogen sulphide and other sulphur impurities negatively affects the operational characteristics of the equipment, contributes

to the development of corrosion, and reduces the purity of the final product. In this regard, an urgent task is to choose the most effective desulphurisation method that ensures minimum sulphur content at optimal economic costs. There are various purification technologies, including absorption, adsorption, and catalytic treatment, each of which

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has certain advantages and limitations. Despite the widespread use of these methods, the issue of their comparative effectiveness remains relevant, depending on the operating conditions and the initial composition of the fraction.

M. Kusenber *et al.* (2022) showed that the use of amine solutions in absorption systems helped to reduce the content of hydrogen sulphide, ensuring high quality of the purified fraction. They also noted that this method proved to be the most effective for large-scale production. N. Sun *et al.* (2023) found that activated carbon adsorption was an economically feasible solution for small and medium-sized enterprises, ensuring a stable reduction in sulphur content. They emphasised that the use of regeneration allowed minimising operating costs. M. Rahmani *et al.* (2023) found that zeolites exhibit high efficiency in removing hydrogen sulphide, even at low concentrations. In addition, they emphasised the resistance of this material to temperature and pressure changes. T. Akashige *et al.* (2024) noted the importance of correctly selecting the operating parameters of absorption systems, such as pressure and temperature, to prevent a decrease in their performance. They concluded that optimising these parameters reduces the energy consumption of the process. H.S. Lau & W.F. Yong (2021) proved that catalytic purification effectively reduced the hydrogen sulphide content to a minimum level, ensuring high purity of the fraction. They also pointed out that the use of expensive catalysts required their regular replacement.

M.A. Zahid *et al.* (2022) pointed out that the introduction of catalytic purification systems was accompanied by high capital costs for equipment and its maintenance. They also noted that the operation of such systems requires qualified personnel. V. Daoo & J.K. Singh (2024) proved that the combination of absorption and adsorption methods allowed achieving the best results in reducing sulphur content. The researchers emphasised that the combination of methods provided a higher degree of purification while reducing costs. C. Becker *et al.* (2022) investigated the effect of the raw material composition on the choice of desulphurisation method, finding that impurities of other gases reduced the absorption efficiency. They concluded that the preliminary preparation of raw materials was a necessary stage of the technological process. Y.-J. Tian *et al.* (2024) showed that the regeneration of adsorbents significantly reduced operating costs and improved the environmental friendliness of the process. They noted that the choice of regeneration method depended on the type of adsorbent used. L. Wu *et al.* (2021) revealed that the absorption method proved to be more effective for large enterprises, while small enterprises obtained better results using adsorption. They came to the conclusion that the scale of production should be the main criterion for choosing a technology. However, despite widespread attention to the problem of desulphurisation, there is a need for additional research aimed at exploring more effective ways to combine purification methods and optimising technological parameters for different production scales. The purpose of the study was to comprehensively compare the effectiveness of various methods of propane-propylene fraction production,

with a focus on their impact on the quality of the final product and economic feasibility for enterprises of different production capacities.

Materials and Methods

The study focused on three main methods: absorption, adsorption, and chemical purification, each of which was analysed from different perspectives, including their applicability to different production scales and environmental impacts. The study is based on theoretical data obtained from the analysis of existing scientific publications and the modelling of desulphurisation processes using various purification methods such as absorption (Georgiadis *et al.*, 2020), adsorption (Nazir *et al.*, 2020), and chemical purification (Ibrahim *et al.*, 2021). In particular, theoretical models describing the kinetics of chemical reactions (Rozanska *et al.*, 2023), the adsorption and absorption properties of materials, and calculations of energy and material costs for the regeneration of solvents and adsorbents were considered (Hatab *et al.*, 2022). These data served as the basis for evaluating the effectiveness of various purification methods and their applicability for different production scales, as well as for predicting operating costs in the long term.

Absorption has been considered as a method for large enterprises, since liquid absorbents such as amines effectively remove hydrogen sulphide from gas mixtures, for example, propane-propylene fraction. Liquid absorption was considered because this method is widely used in industry to remove hydrogen sulphide from gas mixtures. This method is widely used in the petrochemical and natural gas industries due to its high efficiency and low equipment costs, which makes it suitable for enterprises with large production volumes. Adsorption was analysed as the method most suitable for small and medium-sized installations where processing of gas mixtures is limited. Adsorbents such as activated carbon and zeolites, which effectively remove hydrogen sulphide at moderate concentrations, were considered. These materials were chosen because of their ability to provide the required purification in conditions of limited gas volumes.

Chemical purification using oxidising agents and catalysts has been investigated to evaluate its effectiveness in removing hydrogen sulphide. The study also considered catalytic purification as a subspecies of chemical purification. This method was analysed in terms of its ability to provide a minimum sulphur content in the fraction. In addition, the study carried out a theoretical assessment of the quality of the propane-propylene fraction after using various purification methods. Changes in the chemical composition of the fraction were considered, including a decrease in the hydrogen sulphide content, which helped to determine which method most effectively ensures the required quality of the final product. In addition, the potential advantages and limitations of each method in the context of industrial applications were analysed.

A comparison of the economic feasibility of purification methods was carried out to determine their cost effectiveness depending on the scale of production. As part of the analysis, the costs of equipment, operation and

regeneration were considered, which helped to assess which methods are most beneficial for different types of enterprises. Ultimately, environmental aspects were an important part of the study. Possible environmental impacts were considered, including waste disposal, energy intensity of processes and the possibility of reuse of materials, which helped to identify more sustainable and environmentally friendly approaches to desulphurisation.

Results

Desulphurisation is used in the oil and gas industry to purify natural gas and hydrocarbon fractions such as propane-propylene fraction from hydrogen sulphide and other sulphur-containing compounds to prevent corrosion of equipment, improve product quality, and reduce environmental impact. Absorption is a process based on the ability of absorbents, which can be both liquid and solid, to selectively absorb certain components from a gas mixture. In the context of purification of propane-propylene fractions, this method is widely used to remove hydrogen sulphide, the content of which negatively affects product quality, equipment condition, and compliance with environmental regulations. The essence of the method is the contact of a gas mixture with a liquid absorbent, which actively interacts with hydrogen sulphide, converting it to a dissolved state (Shokrollahi *et al.*, 2022). The most common absorbents are amines such as monoethanolamine or diethanolamine, due to their high chemical activity and ability to selectively absorb hydrogen sulphide. The process is usually carried out in an absorption column, where the gas mixture rises up and the absorbent flows down, which ensures maximum contact between the phases. The temperature conditions for effective removal of hydrogen sulphide are usually from 40°C to 60°C, and the pressure – from 1.5 to 2.0 MPa. The concentration of hydrogen sulphide before purification can be 500-1,000 ppm, after which it can be reduced to less than 5 ppm, which is especially important for large installations processing large volumes of raw materials. The chemical interaction between hydrogen sulphide and the absorbent occurs at a high rate, which ensures continuity of the process and high productivity. In addition, the method is universal and suitable for purifying gases with different concentrations of hydrogen sulphide, which makes it in demand at enterprises of various scales. However, there are limitations to this method. One of the key challenges is the need for absorbent regeneration. Over time, liquid absorbents become saturated with hydrogen sulphide and lose their activity, which requires their restoration. The regeneration process is usually carried out at a temperature of 110-120°C and a pressure of 1.0-1.5 MPa, which is accompanied by additional costs for energy, equipment and personnel. Moreover, absorbents are susceptible to chemical degradation under the influence of high temperatures, impurities and acid gases, which shortens their service life and increases operating costs. In addition, the need to recycle used absorbents or their components creates additional environmental risks.

To increase the efficiency of the method and reduce operating costs, it is proposed to use new types of absorbents

with greater resistance to degradation. In addition, the integration of absorption with other methods, such as adsorption or catalytic purification, reduces the load on the absorbents and minimises costs. Despite the existing limitations, absorption remains an indispensable tool in the petrochemical industry due to its high efficiency and versatility. The development of technologies and optimisation of processes provide a sustainable perspective for the use of this method in the future. Adsorption is the process by which solids (adsorbents) absorb molecules or atoms of other substances (such as hydrogen sulphide) on their surface. In the context of purification of propane-propylene fractions from sulphur impurities, the adsorption method is used mainly for small and medium volumes of gas. This method uses adsorbents such as activated carbon and zeolites, which have high adsorption properties and can effectively absorb hydrogen sulphide from a gas mixture at a hydrogen sulphide concentration of up to 1,000 ppm and a pressure of 0.5 to 1.5 MPa. In this case, the temperature during the purification process can range from 30°C to 40°C (Abdirakhimov *et al.*, 2022).

The main feature of adsorption is its ability to work with relatively low volumes of gas. This makes it convenient for use in small enterprises or in cases where purification does not require processing large gas flows (up to 1,000 m³/h). Adsorbents such as activated carbon are porous materials with a huge specific surface area, which makes it possible to effectively capture hydrogen sulphide molecules even at low pressure and low concentrations. This reduces the hydrogen sulphide content in the purified gas to less than 10 ppm. Zeolites, due to their porous structure and ion-exchange properties, can also effectively absorb sulphur compounds, providing another option for gas purification. However, adsorption has its limitations, which may reduce its effectiveness under certain conditions. At high concentrations of hydrogen sulphide (above 1,000 ppm), adsorbents quickly saturate, which reduces their ability to absorb gas and requires frequent regeneration. Unlike absorption, where the absorbent can be used for a long time, adsorbents have a limited-service life in conditions of high concentrations of pollutants. Regeneration of the process, that is, restoring the properties of the adsorbent after saturation, is necessary to extend its service life, but this process is associated with additional costs. Regeneration requires significant energy consumption and the use of temperatures from 200°C to 300°C or the use of chemicals, which leads to increased operating costs. The use of adsorbents entails the need for their disposal after saturation with hydrogen sulphide, which can be environmentally problematic. During operation, adsorbents can accumulate harmful substances, and their safe disposal requires additional steps and resources, which also increases operating costs. This is an important aspect when choosing a purification method, especially in the context of sustainable and environmentally sound production.

Despite these limitations, adsorption remains an important method of purifying hydrogen sulphide gas for small and medium-scale production. To increase the efficiency of adsorption, new types of adsorbents are being

developed, which have improved characteristics such as higher porosity, saturation resistance and the possibility of multiple regeneration. This significantly improves efficiency and reduces operating costs. In particular, the active search for new materials, such as nanomaterials and new types of zeolites, promises to improve the adsorption characteristics and expand the scope of this method. In addition, the combination of adsorption with other purification methods, such as absorption or catalytic purification, can significantly improve the overall efficiency of the process. For example, using pre-adsorption to remove major impurities, followed by absorption or catalytic purification, reduces the burden on each of the technologies and achieves a higher level of purification at lower cost.

Purification from hydrogen sulphide (H_2S) is a key step in processing hydrocarbon gases, including propane-propylene fractions, and its purpose is to minimise the concentration of hydrogen sulphide, which is toxic, corrosive and has an unpleasant odour. Hydrogen sulphide can damage equipment, disrupt technological processes, including polymerisation, and create health problems for people working at such facilities. In particular, the presence of hydrogen sulphide in the propane-propylene fraction can negatively affect the polymerisation process, leading to the development of undesirable by-products and a decrease in the quality of the final product. This makes it especially important to effectively remove hydrogen sulphide to maintain the stability of the process and ensure safe working conditions. Several methods are used for effective purification, including chemical purification using oxidising agents and catalytic processes that remove hydrogen sulphide to minimum concentrations of 0.1 ppm (Zhang *et al.*, 2021).

Chemical purification uses reagents such as oxygen, nitric acid or hydrogen peroxide, which oxidise hydrogen sulphide, converting it into safe and stable compounds. For example, the oxidation of hydrogen sulphide with oxygen leads to the appearance of sulphur and water. This process allows significantly reducing the hydrogen sulphide content in gases and achieve concentrations that meet environmental standards, such as less than 10 ppm. Oxidising agents can react with hydrogen sulphide quickly, which contributes to a high purification rate and allows this method to be used in production facilities with high productivity (up to 500,000 m^3/h) (Liu *et al.*, 2021).

Catalytic processes, in turn, are a subspecies of chemical purification, but they use special catalysts that accelerate

the reactions of hydrogen sulphide conversion into less harmful substances. Catalysts based on metal oxides, such as copper oxide or iron oxide, are usually used for these purposes. The catalysts ensure that the reaction is carried out under milder conditions – at temperatures from 150°C to 250°C and pressures from 0.5 to 2 MPa, which reduces energy consumption. Catalytic purification can be especially useful for cases where it is necessary to ensure a minimum level of hydrogen sulphide in gases, since the process allows controlling the number of by-products that can form during chemical oxidation, reducing their concentration to less than 1 ppm (Li *et al.*, 2021). Despite the high efficiency of chemical and catalytic purification, these methods require the use of expensive equipment and materials. Oxidising agents and catalysts need specialised installations that can withstand aggressive environments with high concentrations of hydrogen sulphide and other components. For chemical purification, these can be reactors with adjustable temperature and pressure parameters, and for catalytic purification, reactors equipped with highly efficient catalysts. The use of such technologies requires significant capital investments and additional equipment maintenance costs.

Chemical purification and catalytic processes are not without disadvantages associated with the regeneration of catalysts and oxidants. During operation, the catalysts lose their activity over time, which requires their replacement or regeneration. The process of catalyst regeneration can be quite complex and energy-intensive, which increases operating costs. In addition, when using oxidising agents, it may be necessary to reduce them, since they decompose during the reaction. These problems lead to higher operating costs and may require additional technical solutions for efficient recovery and continued use of catalysts and oxidants. In addition, by-products of oxidation or contamination of catalysts may require disposal, which adds an environmental burden to the process. Residual substances may include sulphur or other chemical compounds that need to be disposed of safely, which creates additional difficulties for environmental control and may increase waste treatment costs. The quality of the purified fraction is the most important parameter in the processing of hydrocarbon gases such as propane-propylene fraction. One of the key aspects of quality assessment is the content of sulphur, in particular hydrogen sulphide. Therefore, the choice of a purification method that guarantees a minimum sulphur content is crucial for obtaining a high-quality fraction (Table 1).

Table 1. Degree of reduction of sulphur content and the effect on the quality of the final fraction

Purification method	Degree of sulphur reduction, %	Quality of the final fraction
Absorption	90-99	High-quality fraction, with virtually no hydrogen sulphide, is suitable for most applications
Adsorption	85-98	Purity of the fraction is high, but may depend on the type of adsorbent and the operating conditions
Catalytic purification	85-95	Suitable for obtaining high-quality fractions, but may be less effective at high concentrations of hydrogen sulphide
Chemical purification	80-95	Purity may vary depending on the concentration of hydrogen sulphide and the process conditions

Source: compiled by the authors based on D. Ucar *et al.* (2021)

Absorption and adsorption are among the most effective methods for obtaining high-quality fractions with minimal sulphur content. The quality of purification depends on factors such as the absorption temperature, the concentration of the absorbent, the gas flow rate, and the pressure in the system. In addition, the pH of the solvent plays an important role, which affects the efficiency of hydrogen sulphide binding, and the time of gas contact with the absorbent, which can be optimised considering these variables to achieve the maximum degree of sulphur removal. This method, in particular, is ideal for purifying gases from hydrogen sulphide, providing practically pure products. Adsorption using solid adsorbents such as activated carbon or zeolites has also demonstrated high efficiency in purifying gas from hydrogen sulphide, providing a qualitative reduction in the sulphur content in the final fraction. These methods help to achieve extremely low levels of hydrogen sulphide, which contributes to high purity and compliance with environmental standards.

Unlike absorption and adsorption, chemical purification, although effective under certain conditions, is not always able to provide the same level of purification, especially at high concentrations of hydrogen sulphide. Chemical purification methods using oxidising agents or catalysts may require more complex conditions to completely remove hydrogen sulphide. For example, at high concentrations

of hydrogen sulphide, catalysts can quickly saturate, which reduces their effectiveness. In some cases, chemical purification may lead to the development of by-products that may negatively affect the quality of the fraction and require additional purification steps. This limits the possibilities of chemical purification to obtain fractions with a minimum sulphur content. In addition, when using chemical purification, there may be problems with reaction control, especially under changing conditions such as pressure and temperature. The chemical reactions on the basis of which hydrogen sulphide is removed may require precise regulation of these factors to avoid excessive or insufficient oxidation, which may affect the final quality of the fraction. In such cases, purification will not always be as effective as absorption or adsorption methods, which increases the risk of non-compliance with the required quality standards.

When choosing a method for purifying gas from hydrogen sulphide, an important factor is not only the efficiency of the process, but also its economic feasibility. The cost of operation and investment in equipment significantly depends on the volume of gas to be treated and on the choice of the technology itself. In this regard, it is important to consider purification methods such as adsorption, absorption, catalytic and chemical purification from the standpoint of their economic benefits for different volumes of processed gas (Table 2; Table 3).

Table 2. Costs of hydrogen sulphide purification methods

Parameters	Absorption	Adsorption	Chemical purification	Catalytic purification
Equipment cost (USD)	130,000-250,000	40,000-80,000	90,000-180,000	180,000-400,000
Hardware installation (USD)	20,000-40,000	8,000-15,000	15,000-30,000	35,000-80,000
Energy (USD/1,000 m ³ of gas)	10-20	5-10	8-15	5-10
Materials (USD/1,000 m ³ of gas)	Absorbents: 80-150/tonne	Adsorbents: 1,000-1,500/tonne	Reagents: 40-80/tonne	Catalysts: 800-1,200/tonne
Staff (USD/month)	1,000-2,000	700-1,200	900-1,800	1,200-2,500
Regeneration (USD)	40-80/tonne of absorbent	150-250/tonne of adsorbent	Not required	70-120/kg of catalyst
Disposal (USD)	8/tonne of absorbent	40/tonne adsorbent	4/tonne of by-products	15/kg of catalyst

Source: compiled by the authors based on F.J. Alguacil (2023)

Table 3. Cost allocation by enterprise scale (total monthly costs)

Scale of enterprises	Absorption (USD)	Adsorption (USD)	Chemical purification (USD)	Catalytic purification (USD)
Small (10,000 m ³ /day)	~3,000-5,000	~2,500-3,500	~2,800-4,000	~2,200-3,200
Average (50,000 m ³ /day)	~15,000-20,000	~10,000-12,000	~12,000-15,000	~9,000-12,000
Large (500,000 m ³ /day)	~150,000-200,000	~100,000-130,000	~110,000-140,000	~90,000-120,000

Source: compiled by the authors based on T. Yu *et al.* (2022)

Adsorption is one of the most cost-effective purification methods for small volumes of gas. The cost of equipment and installation for adsorption is significantly lower than for more complex methods such as absorption, catalytic or chemical purification. During the adsorption process, there is no need for complex infrastructure or expensive liquid reagents, which makes this method attractive for small and medium-sized enterprises, and for

installation in small production facilities. Due to its simplicity and cost-effectiveness, adsorption minimises the cost of equipment and operation, which is especially important for enterprises with limited budgets.

While adsorption is well suited for small volumes of gas, absorption and catalytic purification prove to be more cost-effective for large volumes of gas treatment. These methods provide high purification efficiency, which makes

them preferable for large installations and enterprises with large production capacities. Absorption using liquid absorbents such as amines can process significant volumes of gas, quickly and efficiently removing hydrogen sulphide. However, such installations require more complex and expensive reactors, and regular replacement and regeneration of absorbents, which increases operating costs. The cost of equipment and maintenance of the absorption plant can be high, but with large volumes of gas, this is justified, since the process allows achieving the required fraction quality and meeting environmental standards.

Catalytic purification, in turn, is used mainly for large industrial facilities, where it is necessary to ensure not only a high degree of purification, but also constant process efficiency. The catalysts used in this process also require regular replacement or regeneration, which increases maintenance costs. Nevertheless, this method can be economically beneficial for large enterprises, as it allows for stable operation with high volumes of gas and minimises the impact of hydrogen sulphide on the environment and equipment. As in the case of absorption, investments in the installation and operation of equipment for catalytic purification can be significant, but for large volumes of processing they are justified due to high productivity and efficiency. For chemical purification, the economic feasibility depends on the scale of production and the frequency of reagent requirements. With small volumes of gas, this method can be effective, but requires ongoing costs for chemicals and waste disposal. For medium and large volumes, chemical purification can justify the cost, especially with a high degree of purification and improved quality of the final product, but this is associated with high capital and operating costs. The processes of gas purification from hydrogen sulphide play an important role in industry, especially in petrochemical production, where a high degree of purification is required to obtain high-quality hydrocarbon fractions. An important aspect of choosing a method is not only its effectiveness, but also its environmental impact, and operating costs, which include energy costs, maintenance costs, and waste disposal.

Absorption has significant environmental and operational aspects. Solvent regeneration requires significant energy consumption and can lead to the development of waste that needs to be disposed of. The cost of such processes also increases due to the need for constant replacement of the absorbent, which leads to additional operating costs. The chemical solvents used can negatively affect the environment if improperly disposed of, which is an important environmental factor. Adsorption, in turn, is a more environmentally friendly method, as solid adsorbents such as activated carbon or zeolites can be recycled or reconstituted, which significantly reduces waste. This method also requires fewer chemicals and is generally less energy intensive than absorption. However, the adsorbent is rapidly saturated at high concentrations of hydrogen sulphide, which requires its regular replacement or regeneration. This increases operating costs, although the overall economic efficiency remains relatively high for small and medium-sized volumes of gas.

Catalytic purification requires more expensive equipment and complex maintenance processes. The catalysts used can be toxic and susceptible to contamination, which creates additional environmental risks. Regular replacement of catalysts and the high cost of their maintenance significantly increases operating costs. Chemical purification, in turn, can be very effective for removing hydrogen sulphide, but it also carries environmental risks associated with the use of oxidising agents and chemicals that can form toxic waste. To prevent environmental pollution, it is necessary to strictly control processes and dispose of chemical waste, which adds to the cost of operation.

Discussion

The study examined various desulphurisation methods to improve the quality of the propane-propylene fraction, including absorption, adsorption, and chemical purification. The results showed that each method has its own characteristics and limitations, which directly affects the efficiency of the purification process and, ultimately, the quality of the final product. Absorption has shown the best results in terms of hydrogen sulphide removal. However, its effectiveness has been reduced by the need for frequent solvent regeneration, which increases operating costs and leads to waste generation. Nevertheless, it remained preferred for large volumes of gas, where other methods may not always be as effective. This problem was also investigated by C. Wang *et al.* (2022), where the results confirmed that the efficiency of absorption in removing hydrogen sulphide for large volumes of gas depends on the correct choice of absorbent and optimisation of the process. For large gas flows, parameters such as flow velocity, temperature, and hydrogen sulphide concentration in the gas must be considered to achieve a high degree of removal. The use of modern absorbers, such as multi-stage speakers, can significantly increase the efficiency of the process.

The study by S. Gilassi *et al.* (2020) also showed that solvent regeneration during the absorption process plays an important role in reducing operating costs, as it allows for repeated use of the solvent. However, frequent regeneration requires significant energy expenditure, which can increase the cost of operation. It is important to choose a regeneration mode that optimises the balance between energy costs and the required process performance. Notably, the efficiency of absorption in removing hydrogen sulphide directly depends on the correct setting of process parameters such as pressure, temperature, and concentration of hydrogen sulphide in the gas. For large volumes of gas, highly efficient absorbers are needed, which can ensure stable operation under changing operating conditions. It is also important to consider the specifics of the gas composition, since the presence of other components, such as carbon dioxide or water vapour, can affect the absorption process and require additional system settings to maximise the efficiency of hydrogen sulphide removal.

The adsorption has demonstrated good results for small and medium volumes of gas, providing a significant reduction in the content of hydrogen sulphide. Unlike

absorption, adsorption uses solid adsorbents such as activated carbon and zeolites, which makes the process environmentally friendly. However, adsorbents are rapidly saturated at high concentrations of hydrogen sulphide, which requires regular replacement or regeneration of the adsorbent. As a result, the operating costs of this method turned out to be higher than expected, especially when working with large volumes of gas. Q. Wang *et al.* (2022) concluded that adsorption is an effective method for removing hydrogen sulphide from small and medium volumes of gas, especially when a high degree of purification is required. One of the main advantages is the ease of installation and operation of the absorbers, which makes this method attractive for small businesses. However, a limitation is the need for frequent adsorbent regeneration, which can increase operating costs and energy requirements, especially with a large volume of gas treatment.

The study by A. Golmakani *et al.* (2022) revealed that the environmental aspects of adsorption during desulphurisation include minimising hydrogen sulphide emissions into the atmosphere and reducing environmental pollution. Operational aspects are associated with high costs for adsorbent replacement and the need for proper process control to ensure its sustainability. On the other hand, adsorption has a relatively low environmental impact compared to other purification methods such as absorption, as it does not require the use of chemical solvents. These results confirm the above study, as they show that adsorption is effectively used to purify small and medium volumes of gas, providing a high degree of hydrogen sulphide removal. In addition, as in the previous analysis, the results indicate the importance of optimising process parameters such as temperature and pressure to increase efficiency. Despite this, as mentioned earlier, the need for frequent adsorbent regeneration and the associated energy load remains the main limitations of this method. Chemical purification, applied to achieve the maximum degree of purification, has demonstrated good results in reducing the hydrogen sulphide content in the fraction. However, this method required the use of oxidising agents, which led to additional costs for chemicals and waste disposal. In addition, the regeneration of catalysts and oxidants can create additional problems with the operation of the equipment. Despite these difficulties, chemical purification was effective in achieving higher fraction quality at low concentrations of hydrogen sulphide.

The study by H. Abedini *et al.* (2021), also found that chemical purification used to reduce the hydrogen sulphide content in the propane-propylene fraction is based on reactions with chemical reagents that effectively remove hydrogen sulphide from gas mixtures. This method allows achieving high levels of purification, which is especially important for improving the quality of the final product and compliance with environmental standards. However, the efficiency of the process depends on the correct choice of catalysts and chemicals, and on the conditions under which purification takes place, such as temperature and pressure. In turn,

Y. Gao *et al.* (2021) concluded that the problems associated with the regeneration of catalysts during chemical purification include their gradual loss of activity and the need for frequent replacement or restoration. Regular regeneration of catalysts requires significant energy consumption, which increases the operating costs of the process. In addition, it is not always possible to restore the catalysts to their original level of efficiency, which can lead to additional costs for their replacement and reduce the overall profitability of the chemical purification process. These data are consistent with the theses given in the previous section, as they confirm that chemical purification is an effective method for reducing the hydrogen sulphide content in the propane-propylene fraction, providing a high degree of purification. Moreover, as discussed earlier, the choice of catalysts and reagents plays a key role in the efficiency of the process, which is confirmed by the results showing a significant improvement in the quality of the final product. However, as mentioned above, the cost of catalyst regeneration and the need to replace them remain significant problems, which limits the long-term economic efficiency of this method.

The results showed that when assessing the effectiveness of various methods, an important factor is not only the degree of purification, but also the effect on the final fraction. In particular, absorption and adsorption ensured a low sulphur content in the final fraction, which is important for improving the quality of the propane-propylene fraction, especially in the chemical industry. Unlike these methods, chemical purification did not always provide such high fraction quality, especially at high concentrations of hydrogen sulphide. This indicates the need for careful selection of the method depending on the required product quality. Y.H. Chan *et al.* (2022) also conducted a study, the results of which showed that when comparing purification methods by the degree of reduction of sulphur content in a fraction, different technologies may demonstrate different levels of efficiency in removing hydrogen sulphide. For example, chemical purification and absorption can provide higher performance than adsorption, depending on the selected reagents and process conditions. However, each of these solutions has its advantages and limitations, which requires careful evaluation to select the most appropriate method, depending on the gas composition and technological requirements. F. De Meyer & C. Bignaud (2022) also found that the effect of purification methods on the final quality of the propane-propylene fraction is directly related to the efficiency of hydrogen sulphide removal, since the presence of sulphur can degrade the quality of the product and increase its cost. Methods that ensure high sulphur removal, as a rule, lead to an improvement in the properties of the fraction, making it more suitable for further use in the chemical and petrochemical industries. Moreover, the use of different purification methods may affect other parameters of the fraction, such as boiling point or impurity content, which is important to consider when evaluating the overall efficiency of the process.

Comparing the data obtained during the research, it can be noted that different purification methods show different degrees of effectiveness in reducing the sulphur content in the propane-propylene fraction, due to the specific features of the technologies used. In particular, chemical purification and absorption are more effective than adsorption, especially at high concentrations of hydrogen sulphide in the gas. However, it should be borne in mind that each method has its own limitations, such as the high cost of reagents or the need for regular regeneration of catalysts, which may affect the choice of the optimal process for specific production conditions. The economic feasibility of using various methods also proved to be a key factor. Absorption and chemical purification, although they provided high purification efficiency, required significant costs for equipment, reagents, and regular regeneration, which could increase the cost of operation. In turn, adsorption was more advantageous for small volumes of gas, but its economic efficiency decreased with increasing volumes and concentrations of hydrogen sulphide. This highlights the importance of choosing a method based on the scale of production and economic feasibility. Y. Lyu *et al.* (2021) concluded that the economic aspects of absorption and chemical purification require considering not only the costs of equipment and reagents, but also additional costs for energy, operation and regeneration. Absorption, despite its high efficiency in removing hydrogen sulphide, may require significant costs for solvent regeneration and maintaining optimal process conditions. Chemical purification also involves high costs for chemicals and waste disposal, which makes an assessment of the economic feasibility of each method important for choosing the optimal technology.

When analysing the results of the study, it becomes clear that the choice between absorption and chemical purification depends on specific operating conditions, such as the volume of gas, its composition and requirements for the degree of purification. Absorption can be more beneficial with small volumes of gas, as it requires lower capital and operating costs. However, for large volumes, where a high degree of purification and regular solvent regeneration are required, chemical purification can be more effective, despite higher operating costs. In general, the results of the study showed that in order to improve the quality of the propane-propylene fraction, it is necessary to carefully choose the purification method depending on a number of factors, including gas volumes, hydrogen sulphide concentration, and quality requirements for the final product. Although each method has its advantages and disadvantages, a combined approach involving pre-adsorption or absorption followed by chemical purification may be the most effective for achieving optimal results under various production conditions.

Conclusions

Absorption has shown high efficiency in removing hydrogen sulphide, especially at high volumes of gas. This method

helps to achieve a significant reduction in the sulphur content in the fraction, which is important for the quality of the final product. However, the use of absorption is associated with high operating costs, as the process requires constant solvent regeneration, which increases the need for additional resources. In addition, waste is generated during the regeneration process, which can have a negative impact on the environmental situation if measures are not taken to dispose of it. The adsorption method, in turn, has shown good results for small and medium volumes of gas. Solid adsorbents such as activated carbon or zeolites can effectively absorb hydrogen sulphide and can also be reused, making this method more environmentally friendly. However, at high concentrations of hydrogen sulphide, adsorbents quickly saturate, which requires their frequent replacement or regeneration. This leads to an increase in operating costs, which, in turn, limits the use of this method for large-scale production. Chemical purification provided the greatest reduction in the content of hydrogen sulphide and allowed obtaining fractions with a minimum sulphur content. However, this method also involves high costs for chemicals and the need for waste disposal. Regular replacement of catalysts and oxidants adds additional operating costs, which reduces its economic feasibility for large volumes of gas.

Cost analysis has shown that adsorption is the most cost-effective method for small and medium-sized enterprises due to low initial investments and moderate operating costs, while absorption is preferable for large enterprises due to its high productivity. Chemical purification and catalytic purification provide versatility and efficiency, but their use is limited by specific requirements: the former is characterised by significant reagent costs, and the latter is justified only for enterprises with strict requirements for gas quality. As a result of the study, it was found that in order to obtain optimal results in the purification of the propane-propylene fraction, it is important to consider the scale of production and the quality requirements of the final product. Absorption and chemical purification prove to be most effective for large volumes of gas, but require significant capital investment and operational costs. Adsorption is economically advantageous for small and medium volumes of gas, but its efficiency decreases at high concentrations of hydrogen sulphide. A combined approach using several methods may be the most effective solution to ensure both high purification efficiency and lower operating costs. To further improve the efficiency of desulphurisation processes, it is necessary to conduct an empirical study of the effect of different types of absorbents and adsorbents on the degree of purification at different temperatures and pressures.

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Conflict of Interest

None.

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Ефективність різних методів сіркоочищення для підвищення якості пропан-пропіленової фракції

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Анотація. Дослідження проведено з метою визначення найбільш ефективного та економічно обґрунтованого методу десульфурації нафтогазових родовищ, що забезпечує мінімальний вміст сірчистих сполук у пропан-пропіленовій фракції. У цьому дослідженні було проведено порівняння методів абсорбції, адсорбції та хімічного очищення, в тому числі каталітичного, з точки зору ефективності видалення сірководню, економічної доцільності та впливу на кінцеву якість пропан-пропіленової фракції. У результаті аналізу було встановлено, що ефективність різних методів сіркоочищення пропан-пропіленової фракції залежить від початкової концентрації сірководню, технічних характеристик обладнання та економічних умов експлуатації. Абсорбційні методи з використанням розчинів амінів показали найвищий ступінь очищення, знижуючи вміст сірководню до менш ніж 5 ppm для великих обсягів газу. Однак значні витрати на регенерацію абсорбенту знижують їх економічну привабливість. Адсорбція з використанням цеолітів та активованого вугілля продемонструвала високу ефективність при обробці малих та середніх обсягів газу. Водночас досягається зниження вмісту сірководню до 10 ppm, а регенерація адсорбенту можлива без значних витрат, що робить метод кращим для невеликих установок. Каталітичне очищення з використанням окислювачів виявилось менш ефективним при високих концентраціях сірководню, але забезпечує стабільну роботу при низьких рівнях домішок. Цей метод вимагає значних капітальних вкладень, але дозволяє отримувати фракцію з вмістом сірки менше 8 ppm. На основі отриманих даних встановлено, що вибір оптимального методу сіркоочищення визначається масштабами виробництва і прийнятними економічними витратами. Абсорбція є кращою для великих підприємств, тоді як адсорбційний метод є оптимальним для малих установок

Ключові слова: абсорбція; цеоліти; адсорбція; активоване вугілля; каталітичне очищення

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