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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DEVELOPMENT OF TECHNOLOGICAL SOLUTIONS TO ELIMINATE PROBLEMS ARISING DURING DRILLING OF INCLINED-HORIZONTAL WELLS

Specialty: 2523.01 - Well drilling technology

Field of science: Technical sciences

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GENERAL CHARACTERISTICS OF THE WORK

Relevance of the topic and the degree of its development. Currently, the drilling of directional and horizontal wells is among the most effective methods for developing oil and gas fields, geothermal resources, and reservoirs with hard-to-recover reserves. The shift towards the exploitation of complex reservoirs characterized by depleted formations, low reservoir pressures, high rock hardness, and significant depths imposes increasingly stringent requirements on drilling technologies and equipment. At the same time, field experience demonstrates that the increased complexity of well trajectories and drilling conditions substantially raises the likelihood of complications such as wellbore instability, loss of drilling fluid circulation, formation losses, drill string sticking, difficulties in wellbore cleaning, and premature wear of drilling tools. These factors lead to significant economic losses, increased non-productive time, and reduced overall drilling efficiency.

Despite advances in drilling technology and a substantial body of published research, challenges remain regarding the prediction and timely prevention of drilling complications in the presence of geological faults, complex spatial wellbore curvature, and extended idle periods. A key objective of both theoretical and practical importance is the development and improvement of methods and technical solutions that enable the timely prediction, control, and minimization of complication risks during the drilling of directional and horizontal wells.

Effective management of hydrodynamic parameters and the selection of optimal drilling fluid density are necessitated by the critical impact of in-situ rock stress on wellbore stability and the occurrence of operational incidents. Of particular relevance is the task of enhancing the accuracy of pressure loss prediction, which arises with variations in inclination and azimuth angles along directional and horizontal well sections, as well as the development of new approaches for calculating sticking forces, taking into account the spatial curvature of the wellbore trajectory.

Existing technical solutions for cuttings transport and removal in complex wellbore trajectories demonstrate limited effectiveness, especially at inclination angles exceeding 30°, where the quality of wellbore cleaning decreases markedly. Therefore, the development and implementation of new bottomhole assembly designs and specialized drilling fluids that ensure efficient cleaning of horizontal and highly deviated well sections are pressing issues.

Special emphasis is placed on research related to drilling in challenging geological conditions, particularly in reservoirs with low formation pressures and in geothermal fields. Elevated temperatures, increased rock hardness, and high risks of drilling fluid losses require new methods of control and artificial maintenance of formation pressure. Currently available methods for creating artificial backpressure in loss zones have several drawbacks, including difficulties in pressure regulation and significant consumption of process fluids, highlighting the need for new, more effective and reliable technologies.

Thus, the relevance of this dissertation is defined by the necessity to develop and improve drilling methods for directional and horizontal wells, aimed at enhancing wellbore stability, minimizing complication risks, efficiently addressing drilling fluid losses, and improving well cleaning processes. Achieving these objectives will substantially increase the technological and economic efficiency of drilling operations in complex reservoirs with depleted and hard-to-recover reserves, as well as in geothermal fields, thereby underscoring the significant scientific, technical, and practical value of this research.

Object of the Study. The process of drilling deviated and horizontal wells under challenging geological and technical conditions, accompanied by risks such as wellbore instability, operational complications, drilling fluid losses, and inefficient cuttings removal.

Subject of the Study. Methods, technical solutions, and physico-hydrodynamic regularities aimed at improving wellbore stability, enhancing wellbore cleaning efficiency, and minimizing complications during the drilling of deviated and horizontal wells.

Research Objective. The objective of this study is to develop and justify engineering and technological solutions aimed at improving the efficiency and reliability of directional and horizontal drilling by optimizing trajectory control parameters, cuttings removal, hydraulic regimes, and minimizing complications associated with spatial curvature and wellbore instability.

Main Research Tasks.

To achieve this objective, the following tasks must be addressed:

- Analyze the geological, technical, and trajectory-related causes of complications arising during the drilling of deviated and horizontal wells, including the influence of tectonic faults, formation dips, and spatial wellbore curvature.
- Investigate the resistance forces acting on the drill string while drilling through curved wellbores and determine their dependence on inclination angles, weight on bit, and drilling fluid properties.
- Develop and introduce a wellbore trajectory quality coefficient reflecting the accuracy of trajectory control, and establish its relationship with drilling efficiency and resistance forces.
- Study hydrodynamic pressure losses in deviated and horizontal well sections, assess the impact of inclination and azimuth angles, and propose corrective formulas for calculating circulation parameters.
- Conduct numerical and laboratory modeling of cuttings transport processes, identify critical parameters influencing the formation of stable cuttings beds, and justify circulation regimes that ensure effective wellbore cleaning.
- Develop mathematical models for calculating the time and velocity of particle ascent in deviated and horizontal wellbores, determine the conditions for cuttings bed formation, and formulate engineering recommendations for preventing related complications.
- Substantiate a methodology for restoring wellbore passability after prolonged shut-ins, taking into account hydrodynamic and mechanical factors affecting the formation of sloughing, filter cakes, and stuck pipe incidents.
- Develop a method for creating artificial backpressure in loss zones by injecting into an adjacent well, carry out its computational validation, and formulate practical application conditions.

Research Methods. The following research methods were employed in this dissertation: analysis of field data, inclinometric and well logging materials; laboratory modeling of friction processes and resistance to drill string movement; mathematical modeling of rock stress states and filtration processes; numerical calculations within the framework of one-dimensional mechanistic models and computational fluid dynamics; laboratory stand tests simulating cuttings transport processes; and computational-analytical methods for evaluating artificial backpressure parameters in loss zones.

Key Provisions Submitted for Defense:

1. The relationship between wellbore trajectory geometry, geological faults, and drilling parameters has been established, which determines changes in inclination and azimuth angles.

2. A formula has been introduced for calculating the resistance force of the drill string, taking into account the normal load and drilling fluid properties.

3. A formula has been developed and validated for determining the trajectory quality coefficient, which affects the technical and economic performance of drilling operations.

4. The correlation between trajectory geometry and pressure losses has been established; a model for calculating hydrodynamic losses under conditions of spatial wellbore curvature has been proposed.

5. A numerical model for cuttings transport in deviated wellbores, accounting for the rheological properties of the drilling fluid and wellbore profile, has been proposed and implemented.

6. Based on laboratory and field tests, parameters governing the formation and breakdown of cuttings beds have been substantiated.

7. A method for creating artificial backpressure in loss zones has been developed, ensuring pressure stabilization during catastrophic fluid losses.

Scientific Novelty of the Research. The research yielded new scientific results aimed at enhancing the efficiency and reliability of drilling deviated and horizontal wells under complex geological and technical conditions:

1. A comprehensive assessment of the impact of geological and structural factors on wellbore curvature has been carried out. It has been established that tectonic faults, variable formation dip angles, and disrupted stratification cause deviations from the planned trajectory.

Adaptive bottomhole assembly (BHA) configurations and recommendations for preliminary geological modeling have been proposed.

2. A new definition of the wellbore trajectory quality coefficient (K) has been developed and scientifically substantiated. Its quantitative relationship with deviation from the planned trajectory, magnitude of resistance during drill string movement, and risk of sticking has been established. The coefficient is proposed as a universal criterion for evaluating drilling accuracy and efficiency.

3. The mechanisms of resistance force formation during the drilling of deviated wellbores have been investigated. The dependence of resistance on the normal load component, contact with clay filter cakes, and the physico-chemical properties of the drilling fluid has been identified. It has been established that up to 12% of resistance is caused by friction in the contact zone, emphasizing the importance of the lubricating properties of the drilling fluid.

4. An analytical model has been developed for calculating hydrodynamic pressure losses in deviated and horizontal well sections, taking into account inclination and azimuth angles, circulation parameters, and drilling fluid properties. Experimental results demonstrated a reduction in pressure losses by 2–3 MPa when drilling at high inclination angles.

5. A numerical two-layer model for cuttings transport has been implemented, incorporating heat transfer, drilling fluid rheology, and well profile angles. The model allows assessment of the conditions for sediment accumulation, annular blockage, and the transition to complications.

6. Critical parameters determining cuttings removal efficiency have been established: minimum flow rate, viscosity, drill string rotation speed, and annular clearance geometry. Based on these, circulation regimes have been proposed that ensure effective wellbore cleaning and prevent the formation of cuttings beds.

7. Engineering recommendations for restoring wellbore passability after prolonged shut-ins have been developed, including analysis of sloughing, filter cakes, and mechanical sticking. The

methodology accounts for the hydrodynamic and mechanical mechanisms of blockage and has been experimentally validated.

8. The technology for creating artificial backpressure under catastrophic loss conditions has been substantiated and implemented. The method involves injecting fluid into a hydraulically connected shut-in well, ensuring pressure stabilization in fractured, low-permeability formations.

Practical Significance of the Results. The research results enable the design of well trajectories that consider geological faults, calculation and reduction of resistance forces during drilling, prediction and prevention of hydraulic complications, and substantiated selection of circulation parameters and drilling fluids for effective cuttings transport. The developed models and recommendations can be implemented in the design and support of drilling operations in fields with complex geological and physical conditions.

Approbation of the Work. The materials of the dissertation have been presented and discussed at:

- SPE “International Petroleum Exhibition & Conference” (2020, Abu Dhabi, UAE);
- IV All-Russian Scientific and Practical Conference “Oil and Gas Engineering, Technosphere Safety, Rational Use of Natural Resources: Modern Realities” (2021, Dagestan, Russia);
- Bulatov Readings, Proceedings of the VI International Scientific and Practical Conference (March 31, 2022, Krasnodar, Russia);
- Conference Proceedings "Energy Locomotives of the Turkish World" dedicated to the 100th anniversary of the National Leader Heydar Aliyev (25–26 October 2023, Baku, Azerbaijan).

Publications. The main results of the dissertation have been published in 22 scientific works, including 18 articles and 4 conference theses.

Name of the Institution Where the Dissertation Was Completed. The dissertation was carried out at the Research Institute "Geotechnological Problems of Oil, Gas and Chemistry".

Structure and Scope of the Work. The dissertation consists of an introduction, four chapters, conclusions, and appendices. The total length of the work is 175,471 characters. The list of references includes 125 sources.

CONTENT OF THE WORK

The introduction substantiates the relevance of the problem under consideration, formulates the objectives and research tasks of the dissertation, outlines the main scientific contributions and their validity, and demonstrates both the scientific novelty and practical significance of the research findings.

Chapter One of the dissertation presents a systematic and comprehensive analysis of existing scientific publications, studies, and field data related to addressing problems encountered during the drilling of deviated and horizontal wells. Geological, technological, and technical factors that determine wellbore curvature parameters, affect wellbore stability, cuttings removal quality, and the risk of complications are considered. Special attention is given to complications arising from geological disturbances in formations, as well as during prolonged drilling shut-ins, and their relationship to spatial wellbore curvature.

Within the literature review, modern approaches and technological solutions aimed at preventing and eliminating complications encountered while drilling deviated and horizontal wells are examined in detail. Methods for selecting the optimal drilling fluid density, considering in-situ rock stress—a key factor in preventing stuck pipe and borehole collapse—are analyzed. Existing approaches to calculating hydrodynamic pressure losses, accounting for inclination and azimuth angles, as well as the influence of wellbore curvature on drilling hydrodynamics, are also reviewed.

Significant attention is given to assessing existing methods for cuttings transport calculations in deviated and horizontal well sections, including analysis of their impact on cleaning efficiency. Modern bottomhole assembly (BHA) designs and their effectiveness in cleaning horizontal and highly deviated sections are examined. The chapter also reviews approaches for evaluating drill string sticking forces and examines current methods for predicting stuck pipe events in complex wellbore trajectories.

The work further presents an analysis of drilling problems in fields with low reservoir pressures, hard-to-recover reserves, and geothermal resources. The specific features of drilling such targets are studied, including high-temperature conditions, increased rock hardness, equipment erosion, and drilling fluid loss challenges. Both domestic and international experience in using specialized reagents, such as AphronICS and other chemical systems, to combat losses in depleted and low-permeability formations are reviewed.

Technologies and approaches for creating artificial backpressure in loss zones through the injection of fluids into nearby production wells are examined and critically evaluated. The effectiveness of these technologies is assessed, and the need for new technological solutions to ensure more reliable control of drilling fluid losses is substantiated.

Based on the comprehensive analysis conducted, specific scientific and technical tasks have been formulated, the solution of which will improve the efficiency, reliability, and safety of drilling deviated and horizontal wells, as well as reduce the risk of complications and incidents. The justification for the relevance of the research provided in this chapter underscores the scientific and technical significance and practical demand for the proposed tasks, thus highlighting the need for further theoretical and experimental investigations within the present work.

Particular attention in the chapter is given to analyzing the causes of complications such as circulation loss, drill string sticking, inefficient wellbore cleaning, and borehole wall collapse[1]. It is noted that, despite the significant arsenal of available methods and tools for addressing such complications, the timeliness of their application remains a crucial factor for operational success. In this regard, the importance of predictive approaches, analysis of field data, and geomechanical models for risk assessment before drilling operations is emphasized.

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[1] Xianzhi Song, Gensheng Li, Zhengming Xu, Subhash Shah. Fundamentals of Horizontal Wellbore Cleanout: Theory and Applications of Rotary Jetting Technology, 2022. pp. 301-339

Using the example of horizontal well drilling—which has become widespread in the oil and gas industry since the mid-20th century—the particular importance of technologies that ensure wellbore stability and effective cuttings transport is demonstrated. It is emphasized that the most acute problems, such as cuttings deposition on the lower side of the wellbore, formation of stationary beds, increased friction, excessive torque, and even mechanical damage to pipes, typically occur in horizontal and highly deviated sections.

A separate block of text is devoted to describing the flow regimes of the solid phase (cuttings) within the wellbore. Four main flow regimes of the drilling fluid-cuttings mixture are described: fully suspended symmetrical, asymmetrical, moving, and stationary beds. These regimes are closely related to parameters such as wellbore inclination, flow velocity, and drilling fluid viscosity and density.

The chapter highlights that each regime is characterized by its own flow stability conditions and critical velocity values, below which particle settling and blockage formation occur.

The chapter also provides a detailed description of the forces acting on cuttings particles in drilling fluid, including gravity, Archimedes' force, drag, and lift, as well as their influence on particle transport along the wellbore[2].

A summary of types and classifications of drilling fluid additives is provided, describing their purposes—from weighting agents and viscosifiers to fibers and stabilizers. It is noted that effective cleaning of horizontal and deviated wells cannot be achieved without careful engineering of the rheological properties of the fluid, such as yield point and plastic viscosity, which determine the carrying capacity of the fluid.

A key part of the analysis concerns parameters subject to field control: flow rate, fluid viscosity, well inclination angle, drill string rotation speed, as well as design parameters such as pipe eccentricity and wellbore diameter. Each of these has a significant impact on

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[2] Adam T. Bourgoyne Jr., Keith K. Millheim, Martin E. Chenevert, F. S. Young Jr. Applied Drilling Engineering // Society of Petroleum Engineers (SPE Textbook Series) – 1991. Vol.2

cleaning efficiency and successful cuttings transport, especially in complex well trajectories.

The chapter concludes with a review of empirical models and experimental data confirming the influence of various parameters on cuttings transport. It is emphasized that modern drilling requires an integrated approach: not only the careful selection of drilling fluids and tools, but also continuous monitoring, forecasting, and real-time adaptation of drilling parameters. The chapter sets the direction for further research aimed at optimizing drilling processes, reducing non-productive time, and preventing complications at all stages of well construction.

Chapter Two focuses on field investigations of problems arising during the drilling of deviated wells and the development of practical methods for their mitigation. The main focus is on the influence of geological, technological, and technical factors on wellbore curvature, investigation of resistance forces during drill string movement, assessment of trajectory quality, changes in hydrodynamic pressures during wellbore cleaning, and complications arising after shut-ins during drilling operations. The influence of a combination of factors on the curvature parameters of deviated wells is considered using the example of the Neft Dashlary (Oil Rocks) field.

The structure of this field is an asymmetric brachyanticline with sharp changes in formation dip angles (up to 70–80°) and the presence of tectonic faults. It has been established that faults and abrupt changes in formation geometry have a significant impact on wellbore trajectory, as confirmed by inclinometry and well design data (Fig. 1) [11].

During the drilling process, deviations from the planned inclination and azimuth angles are observed, particularly when using the turbine drilling method. These deviations are attributed both to geological features and to the insufficient effectiveness of the selected bottomhole assembly (BHA) configuration.

In several cases, increasing the weight on bit on the bit led to higher hydrodynamic pressure and a reduction in the inclination angle, especially in soft formations where the drill string, under its own weight, tends to rest on the lower side of the wellbore. Methods for correcting drilling angles were proposed, including the use of stabilizers and modifications to the BHA configuration.

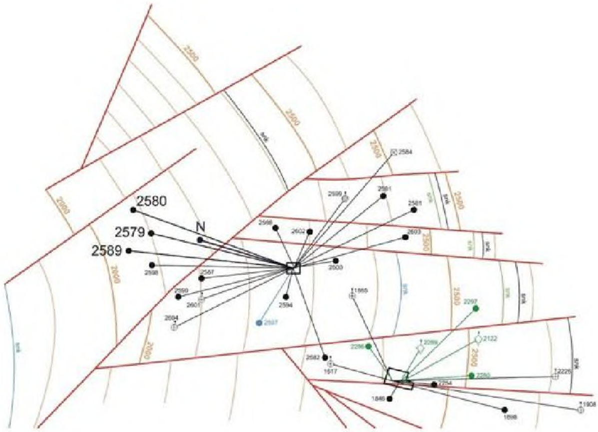

Fig. 1. Structural map constructed for the top horizon, Block V

The mathematical model (Fig. 2) demonstrated the relationship between weight on bit and changes in angles, enabling more effective trajectory control during drilling.

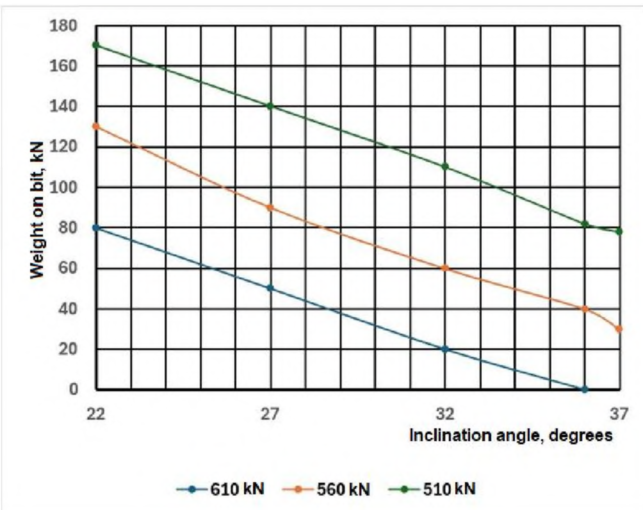

Fig. 2. Graph of the relationship between weight on bit and inclination angle at various hook load values

Below are practical examples of successful trajectory correction when switching from turbine to rotary drilling methods, as well as an analysis of the influence of BHA configuration on the outcome. A comparison with adjacent wells was conducted, confirming the impact of drilling technology and geological factors on trajectory parameters. It was established that, when designing deviated wells, it is necessary to consider formation dip angles and to conduct a preliminary analysis of well log data from neighboring wells. The use of multiple stabilizers and the selection of weight on bit parameters based on mathematical relationships are recommended. It was found that, when transitioning from turbine drilling to rotary drilling, wellbore curvature parameters stabilize.

Section 2.2 of the dissertation is devoted to the study of resistance encountered by the drill string when moving in a curved wellbore [1]. As depth and inclination angle increase, resistance also rises, negatively affecting technical and economic indicators. Three approaches to reducing resistance forces are considered: applying lubricant to the pipe surface, introducing surfactants into the drilling fluid, and developing special drilling fluids with enhanced lubricating properties. In laboratory conditions, the movement of a sample along a clay filter cake in a wellbore was simulated, and the dependence of resistance force on the normal load component was established. The depth of sample penetration and contact area with the clay cake were calculated, allowing for a quantitative assessment of the drilling fluid's influence on friction forces. The experimental data obtained indicate that up to 12% of the total resistance may be attributed to the drilling fluid.

Section 2.3 examines the effect of the wellbore trajectory quality coefficient (K) on resistance forces in deviated wells [4]. Previous methods for determining this coefficient did not account for all trajectory parameters.

In this work, a new formula is proposed that considers the planned and actual lengths, angles, and deviations of the wellbore (Formula 1).

$$K = \frac{L\text{п}\, Sn \cos\varphi}{L\varphi S\varphi} \quad (1)$$

Based on field data from Caspian Shelf fields, a classification of wells was carried out according to the values of the trajectory quality coefficient.

As a result of the analysis, characteristic dependencies were identified, showing how the coefficient varies with depth (Fig. 3) and how the resistance force depends on its value (Fig. 4).

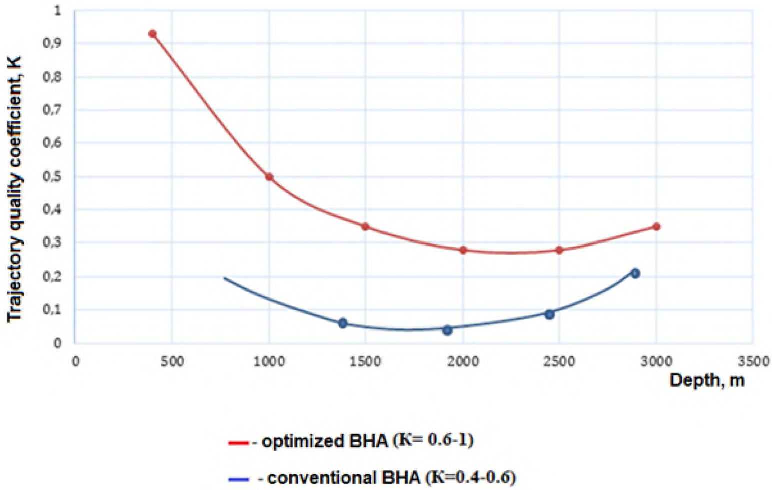

Fig. 3. Variation of quality coefficients with depth

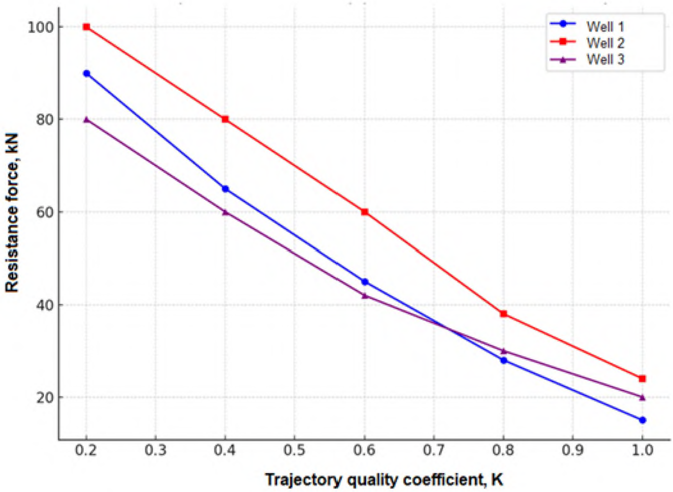

Fig. 4. Relationship between resistance force and quality coefficient (K) for different wells

Section 2.4 of the dissertation examines changes in hydrodynamic pressure during the cleaning of deviated and horizontal wells, depending on inclination angles [12]. It was found that at angles greater than 65°, cleaning efficiency decreases, and the risk of cuttings accumulation and emergency situations increases.

Experimental results demonstrated that, all other conditions being equal, pressure losses in horizontal wells are 2–3 MPa lower than in vertical wells. Formula (2) was obtained, describing the dependence of hydrodynamic losses on the average inclination angle.

$$\Delta P_{d.h} = \frac{\Delta P_v}{1+Sin\alpha_{av}} \quad (2)$$

where, ΔP_v – pressure losses in a vertical well, assuming equal well depth and length of the deviated-horizontal section, MPa;

$\Delta P_{d.h}$ - pressure losses in a deviated-horizontal well, taking into account the average inclination angle, MPa;

α_{av} – average inclination angle, degrees.

Based on a standard three-interval profile, pressure losses were calculated for each interval, allowing for the influence of wellbore geometry to be considered in hydraulic calculations and well design.

Finally, Section 2.5 discusses complications arising after prolonged well shut-ins, such as borehole wall sloughing, clay swelling, formation of loose filter cakes, and sticking incidents [5,6]. An example is given of Well No. 142 in the Gunashli area, where, after a long shut-in and subsequent geophysical operations, a probe and cable became stuck. Borehole remediation was complicated by increased pressure and the risk of formation fracturing. The work describes a step-by-step algorithm for wellbore restoration, including circulation adjustment, control of remediation speed, working the tool free, and relieving excess pressure. This methodology was successfully applied in other wells (No. 270, 64, 67, etc.), confirming its practical effectiveness.

Thus, Chapter Two presents a comprehensive investigation of the problems encountered when drilling deviated wells, with a focus on the practical application of the obtained results to specific fields. The main conclusions highlight the necessity of accounting for geological conditions at the design stage, optimizing the BHA, controlling weight on bit, and applying adaptive drilling schemes to prevent complications and enhance wellbore trajectory efficiency.

Chapter Three of the dissertation presents the results of comprehensive research aimed at the scientific substantiation of technological solutions for improving the drilling of deviated and horizontal wells. Each section of the chapter addresses a specific aspect of engineering and hydrodynamic support for wellbore cleaning, prevention of complications, and optimization of drilling parameters under the current conditions of complex oil and gas field development.

Section 3.1 provides a comprehensive analysis of the features of wellbore cleaning in vertical wells. It is shown that cuttings removal efficiency is determined by a combination of factors, with wellbore geometry, physico-chemical properties of the drilling fluid, circulation regimes, and type of BHA playing key roles [13]. It is noted that there are no universal methods: selecting effective solutions requires an individual analysis of geological and technical conditions, annular geometry, and operational modes. The roles of circulation velocity, fluid viscosity, drill string rotation, eccentricity, and cuttings particle size are discussed in detail (Fig. 5).

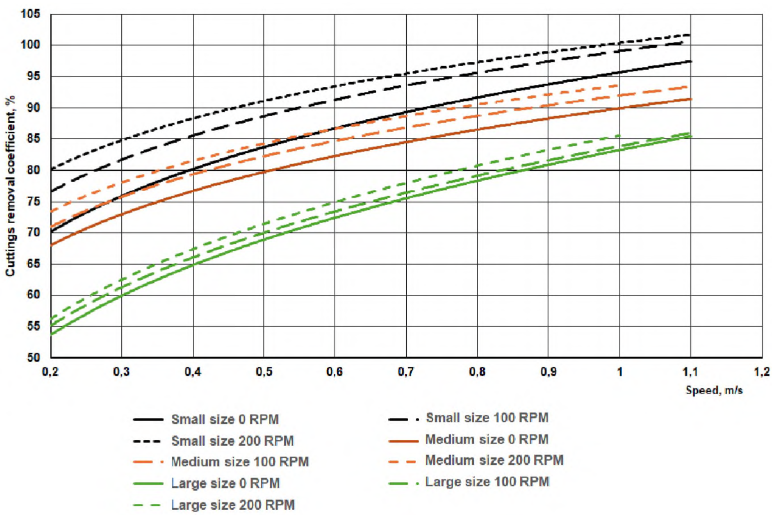

Fig. 5. Simulation results

It is demonstrated that maintaining turbulent flow and properly managing mechanical actions are critically important for preventing cuttings settling and the formation of stagnant zones.

The study analyzes modern approaches to investigating the cuttings removal process, including laboratory experiments, one-dimensional (RT/1D) mechanistic models, and computational fluid dynamics (CFD) methods. Using numerical simulations based on the Herschel–Bulkley model, the high effectiveness of integrating these methods for calibrating cleaning regimes and optimizing fluid properties is substantiated. The simulations show that increasing circulation velocity and optimizing rheological properties of the fluid reduce the risk of cuttings settling, while integrating laboratory and numerical methods provides reliable calibration of computational models. The crucial role of a comprehensive approach to selecting technological parameters and the application of advanced monitoring methods is emphasized [22].

Section 3.2 presents the results of numerical modeling of cuttings transport processes in deviated and curved wells. Specialized software has been developed, implementing a two-layer mathematical model that accounts for heat transfer and fluid properties, allowing assessment of the dynamics of cuttings accumulation and re-entrainment under various operational conditions. The model considers both Newtonian and non-Newtonian rheological properties, initial cuttings concentrations, flow rates and pressures, temperatures, inclination angles, and bit rotation speeds. For practical validation, real well profiles were constructed and calculations performed to assess the impact of rate of penetration, particle size, and pipe connection time on equivalent circulating density (ECD). For the first time, critical time intervals (Fig. 6) have been identified, after which the annular clearance may become plugged by settled cuttings; risks associated with rapid drilling and high cuttings generation rates have been revealed.

This made it possible to develop recommendations for selecting optimal circulation regimes to prevent complications and enhance wellbore stability [15].

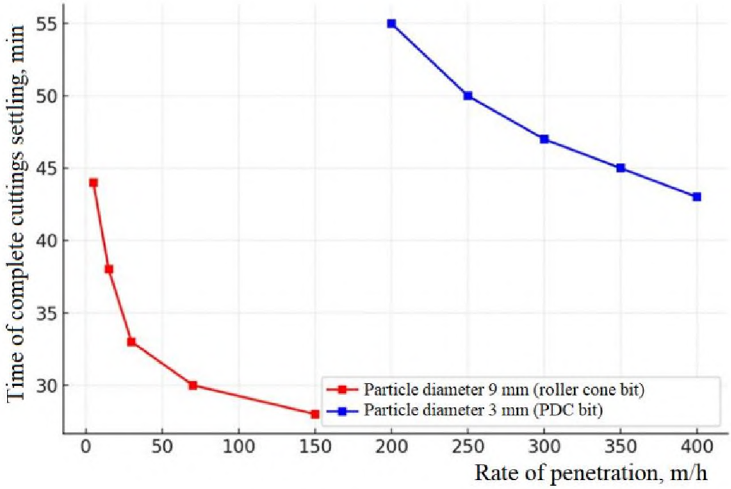

Fig. 6. Dependence of cuttings settling time on rate of penetration

Section 3.3 presents a comprehensive laboratory and numerical investigation of the transport of large cuttings particles in horizontal wells. For physical modeling, a transparent pipe was used, equipped with a system for introducing experimental particles and the ability to adjust flow rate, inclination angle, and drill string rotation speed. For the first time, both experimental and theoretical results have shown that increasing particle size and rate of penetration leads to a sharp increase in cuttings bed thickness and a deterioration in cleaning conditions. It was found that effective mixing and removal of large particles are possible only with the comprehensive optimization of drilling fluid flow rate, viscosity, and drill string rotation speed (optimal values: 80–100 rpm; viscosity 65–75 mPa·s; density up to 1300 kg/m³). Recommendations are provided regarding technological regimes to prevent the formation of hazardous layers and the occurrence of complications (sticking, drag, loss of circulation).

Section 3.4 is devoted to analyzing the particle ascent time during the drilling of deviated and horizontal wells (Fig. 7).

It has been demonstrated that the efficiency of wellbore cleaning is determined not only by the properties of the drilling fluid, but also by the inclination angle, wellbore profile, circulation regime, and the dynamics of equivalent circulating density.

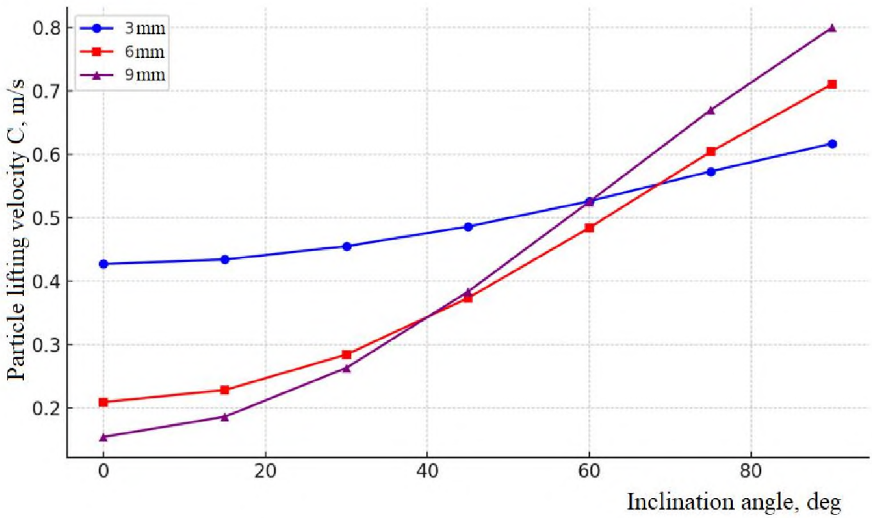

Fig. 7. Particle ascent velocity for different cuttings diameters

Formulas have been developed to quantitatively assess the impact of these parameters on the risk of cuttings accumulation and sticking incidents. An analysis of the effectiveness of mechanical and dispersion cleaning methods was performed, and critical conditions for the formation of stationary layers were identified. Practical recommendations have been formulated for reducing cleaning time and improving the operational reliability of drilling activities.

Section 3.5 examines the influence of curvature in deviated and horizontal wells on the efficiency of wellbore cleaning. It was found that increasing the inclination angle and the length of horizontal sections raises the risks of cuttings accumulation, the formation of stable cuttings beds, mechanical sticking, and loss of circulation.

Section 3.6 is devoted to determining the sticking force with consideration of spatial curvature in deviated wells. For the first time, a method for assessing bending forces arising from changes in inclination and azimuth angles, as well as differential loads, is proposed. Equations have been developed to describe the elastic axis of the drill string, radius of curvature, bending stresses, and the resulting sticking force. It was established that the risk of sticking increases with significant wellbore curvature.

Section 3.7 substantiates the selection of optimal drilling fluid density, taking into account the stress state of rocks in the wellbore[3]. An analysis of the effects of tectonic regime and variations in formation pressure on wellbore stability is performed. Calculation methods for determining rock stresses and the equivalent drilling fluid density are proposed. Recommendations are formulated for selecting density to prevent borehole collapse, blowouts, and losses [8].

Section 3.8 is dedicated to calculating pressure losses in the wellbore when azimuth changes and spatial curvature are present. An approach has been developed for the accurate determination of hydraulic losses in bent well sections. A comparison of design and actual data confirmed a significant increase in pressure losses in wells with complex trajectories, which must be considered in hydraulic calculations and when selecting pumping equipment.

Overall, the studies conducted in Chapter Three comprehensively address all key aspects of ensuring the technological and operational reliability of drilling deviated and horizontal wells, integrating the results of modeling, laboratory experiments, and analysis of modern technical solutions to form a scientific basis and practical recommendations aimed at minimizing complications and increasing the efficiency and safety of drilling operations.

Chapter Four discusses the theoretical and practical aspects of drilling wells in complex geological conditions characteristic of fields with abnormally low reservoir pressure and hard-to-recover reserves. Particular attention is paid to three key areas: geothermal well drilling, drilling in depleted reservoirs with catastrophic drilling fluid losses, and the application of AphronICS reagents for wellbore stabilization and loss mitigation [3].

Section 4.1 of the abstract provides a detailed examination of complications encountered during drilling in geothermal fields and

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[3] Mark D. Zoback. Reservoir Geomechanics (Unit: Wellbore Stability) // Cambridge University Press, 2007. pp. 301-339

modern methods for their resolution. It is noted that geothermal drilling is associated with a number of specific challenges: circulation losses due to fractured formations, wellbore instability, and difficulties with cementing[4]. Circulation losses not only result in financial costs but can also lead to serious complications, such as stuck pipe, borehole collapse, and premature failure of casing strings. High temperatures and aggressive environments reduce the reliability of drilling equipment and degrade cement properties, increasing the risk of mechanical and hydraulic complications. It is concluded that the development of innovative technologies and materials capable of ensuring wellbore stability and effective circulation loss control is essential to improving the reliability and economic efficiency of geothermal drilling.

Section 4.2 describes a unique method for combating drilling fluid losses by creating artificial backpressure in the loss zone, which is achieved by injecting fluid into the formation from a nearby (shut-in) well that is hydraulically connected to the drilling well [2].

Our proposed method consists in maintaining reservoir pressure in the loss zone to prevent drilling fluid from escaping during drilling operations. This approach involves several stages. The first stage is based on identifying a well located a short distance from the drilling well and penetrating the loss zone, but not in operation. This formation must have an underground hydraulic connection between the drilling and production wells, as shown in Fig. 8.

After identifying the well, the second stage begins. This involves specific operations in the selected production well aimed at maintaining formation pressure. Initially, a cement plug is set up to the shoe of the loss zone. After installing the cement plug, perforation is performed in the casing—preferably oriented toward the drilling well and across the thickest part of the formation. To prevent losses, it is essential to keep the pressures in both the formation and the drilling well equal.

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[4] Петров В.А., Иванов С.М. Проблемы и методы борьбы с потерями циркуляции при бурении геотермальных скважин. "Бурение и нефть", 2018, №3, стр. 45-53.

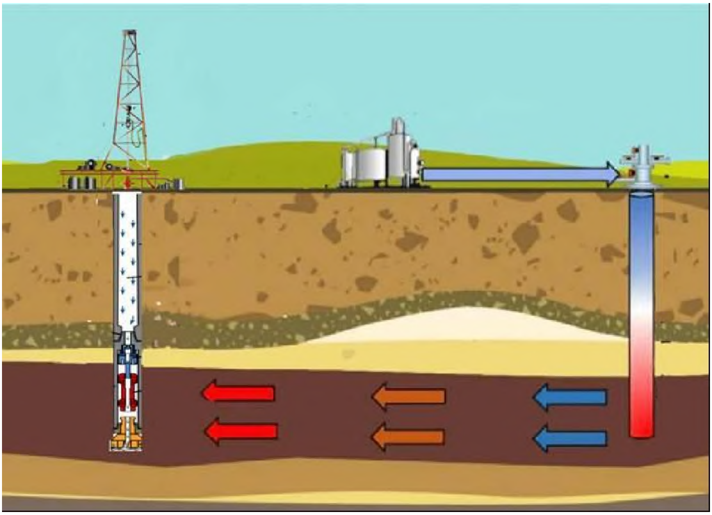

Fig. 8. Method for combating fluid loss

As is known, wellbore pressure can be regulated by adjusting the density and flow rate of the drilling fluid. However, in the case of catastrophic losses, pressure control in the wellbore becomes practically impossible.

The proposed method enables regulation of formation pressure by injecting fluid or gas into the formation to prevent losses. This approach is commonly used to maintain pressure in a well in order to increase production. In our case, however, injection is performed directly into the loss zone. First, it is necessary to determine the pressure in the well during drilling. Subsequently, fluid (drilling mud, water, polymer solutions) with good displacement properties is injected under pressure into the formation through the previously producing well. The required injection pressure is determined based on the pressure in the drilling well.

The volume of drilling mud to be injected and the inlet pressure can be calculated using the Dupuit formula (for radial filtration), which depends on several factors[5].

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[5] Петров С.Н. Расчет объемов и давления бурового раствора при радиальной фильтрации. Нефтяное хозяйство, 2010, №4, стр. 52–60.

$$Q = \frac{2\pi kh(P_{form} - P_{well})}{\mu \cdot ln\frac{R_k}{R_{well}}} \tag{3}$$

Q – injected fluid rate, m³/s;

k – permeability coefficient of the loss zone, Darcy;

h – thickness of the loss zone, m

P_{form} – formation pressure in the loss zone, $\frac{N}{m^2}$

P_{well} -pressure in the selected production well, $\frac{N}{m^2}$

μ - fluid viscosity, $\frac{N \cdot s}{m^2}$;

R_{well} – radius of the selected production well, m;

R_k - boundary radius (distance from the production well to the drilling well), m.

With constant reservoir parameters—η, k, h, R_k, R_{well}—and a given outlet pressure (P_k), it is possible to determine the required inlet pressure (P_{well}) and the necessary injection rate (Q) to maintain it.

$$P_{well} = P_k - \frac{Q \cdot \eta \cdot ln\frac{R_k}{R_{well}}}{2\pi K \cdot H} \tag{4}$$

Thus, by adjusting the volume and properties of the injected fluid, it is possible to control the outlet pressure, maintaining the pressure necessary to prevent drilling fluid loss in the active well.

After drilling through the loss zone in the active well to a certain depth, the casing string is run and cemented, after which drilling operations continue.

In the injection well, a cement plug can be set if further use of the well is not required. If the well remains in use, a packer is installed above the loss zone, which can be removed if necessary.

The proposed method for combating fluid loss will enable qualified specialists to drill wells in fields with heavily depleted reservoirs without significant complications.

CONCLUSIONS

1. Based on field studies of deviated wells (specifically at the Neft Dashlary field), it has been established that geological features such as tectonic faults, variable formation dip angles, and disrupted stratification significantly distort the drilling trajectory. This necessitates the implementation of adaptive bottomhole assembly (BHA) schemes and stabilizers, as well as preliminary geological modeling at the well design stage.

2. A new definition of the trajectory quality coefficient (K) has been introduced, enabling the assessment of deviations between the actual and planned trajectories. It has been found that a decrease in this coefficient leads to increased resistance forces during drill string movement, a higher risk of sticking, and greater mechanical loading on drilling tool components.

3. It has been determined that the resistance force encountered when drilling deviated wellbores directly depends on the normal load component, the nature of contact with the clay filter cake, and the physico-chemical properties of the drilling fluid. Up to 12% of total resistance is shown to be attributable to the contact zone with the fluid, underscoring the importance of its lubricating properties, especially at high contact angles.

4. It has been demonstrated that hydrodynamic pressure losses in deviated and horizontal sections differ significantly from those in vertical sections. Experimental results show that pressure losses at inclination angles above 60–70° can be reduced by 2–3 MPa compared to vertical intervals. A formula has been developed to describe the dependence of losses on inclination angle and circulation parameters.

5. Numerical and laboratory modeling have established that cuttings removal efficiency decreases sharply if critical parameters—drilling fluid flow rate, viscosity, drill string rotation speed, and annular geometry—are not maintained. The conditions for the transition from a suspended regime to the formation of stable cuttings beds have been identified.

6. A two-layer numerical model for cuttings transport has been implemented, accounting for heat transfer, fluid rheological

properties, and well profile angles. Critical time intervals have been established, after which sediment accumulation and annular plugging may occur.

7. As a result of this study, recommendations have been proposed for selecting drilling fluid density, considering the stress state of the formation, tectonic loading regime, and the “density window” range. The conditions for wellbore stability and the prevention of both collapse and fluid loss in complex geomechanical environments have been identified.

8. A new technology for creating artificial backpressure in loss zones, implemented via a hydraulically connected shut-in well, has been substantiated. This method ensures formation pressure stabilization and prevents catastrophic drilling fluid losses, especially in low-permeability fractured formations.

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Personal Contribution of the Applicant:

Works [13, 15] were carried out independently.

In works [1- 6, 7, 9-12, 14, 16-22], the applicant was responsible for conducting experimental research and processing the obtained results.

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