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Research and Evaluation of Efficient Drilling Speedup Supporting Technologies and Cementing Processes for Ultra-deep Wells

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Abstract

This paper conducts research and evaluation on the supporting technology for efficient drilling and acceleration in ultra-deep wells, as well as cementing processes. By reviewing the latest research achievements and technological advancements both domestically and internationally, various technical means related to drilling engineering design, fluid systems, equipment, and operation management are summarized. The applicability and benefits of different techniques are deeply studied through the analysis of multiple practical case studies. Additionally, a comparative analysis of various cementing processes used in ultra-deep well development is conducted to assess their strengths, weaknesses, and applicability. Finally, optimization recommendations for efficient drilling and acceleration technology, as well as cementing processes in ultra-deep wells, are proposed, along with future prospects for the development of ultra-deep well drilling technology. This study provides a scientific basis and technical support for the efficient development of ultra-deep oil and gas resources.

Keywords

Ultra-deep Well; Efficient Drilling; Acceleration Technology; Cementing Process; Evaluation Analysis.

1. Introduction

In China, 39% of remaining oil and 57% of remaining natural gas reserves are distributed in deep reservoirs, such as Keshen, Dabein, Bozi, and Shunbei in the Tarim Basin, and Chuanxin, Chuanzhong, and Chuandong in the Sichuan Basin, as well as the southern margin of the Junggar Basin. These deep and ultra-deep reservoirs have become important strategic areas for oil and gas storage and production enhancement and will be a key focus for increasing reserves and production in the coming years. With the continuous increase in exploration and development efforts and rapid advancement in oil and gas well engineering technology, a series of drilling and completion technologies for deep and ultra-deep wells have been developed, facilitating the advancement of ultra-deep wells beyond 9000 meters. Several landmark wells, such as Pengshen 6, Shuangyu 001-H6, Guole 3C, and Shunbei 801X, have set new records, effectively supporting the exploration and development of deep and ultra-deep reservoirs[1-2].

However, due to the increasing complexity of oil and gas exploration and development targets, well cementing for deep and ultra-deep wells still faces new challenges. Moreover, drilling ultra-deep wells involves long drilling cycles, slow mechanical drilling rates, and complex downhole conditions, severely limiting the development process of deep oil and gas resources. Therefore, continuous research and strengthening of fundamental theories in well cementing for deep and ultra-deep wells, critical materials for high-temperature cementing, wellbore fluid systems, functional cementing tools, as well as supporting processes, and advanced technologies for ultra-deep wellbore designs are required to efficiently accelerate drilling operations. These efforts will provide robust technical support for the exploration and development of deep and ultra-deep oil and gas resources[3].

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As drilling depths continue to increase, the demands on drilling equipment and processes intensify. Simultaneously, more pronounced geological challenges, such as high temperature, high pressure, and high in-situ stresses, will arise, presenting numerous engineering and technical difficulties. For instance, increased casing depths may affect the load-bearing capacity of drilling equipment and limit pump pressure and displacement capabilities. Conventional drilling tools may struggle to meet tensile strength requirements. Additionally, the difficulty of maintaining straight drilling paths under high-temperature conditions may be encountered, and challenges with mud rheology and long-term stability of cement slurries will emerge. The existence of these difficulties will significantly impact the feasibility and success of ultra-deep drilling and completions.

2. Efficient Drilling Speedup Supporting Technologies at Home and Abroad

2.1. Status and Challenges of High-efficiency Drilling and Speeding-up Technologies for Ultra-deep Wells

Currently, oil and gas exploration and development face severe challenges, such as declining resource quality, increased complexity of oil and gas targets, and stringent safety and environmental regulations. As a result, global oil and gas exploration and development are shifting towards deep and ultra-deep reservoirs. In this context, drilling and completion technologies for deep and ultra-deep wells also encounter new difficulties and challenges.

By developing a series of speeding-up tools, including high-efficiency PDC (Polycrystalline Diamond Compact) drill bits, composite drill bits, impregnated drill bits, high-temperature resistant screw drilling tools, equally thick-walled screw drilling tools, metal screw drilling tools, turbine drilling tools, hydraulic pulse rock-breaking tools, and energy-saving and speeding-up navigation systems, these technologies have gradually become the mainstay for speeding up drilling in deep and ultra-deep wells. Continuous improvement in the supporting technologies for fast and efficient drilling in deep and ultra-deep wells has led to a significant reduction in accident complexity, a substantial decrease in drilling cycles, and effective support for increased oil and gas reserves and rapid production in key areas such as the Tarim Kuche Front and Chuan-Chong gas regions[4-5].

The biggest challenges faced by deep and ultra-deep wells mainly lie in the difficulty of drilling in dense deep and ultra-deep rock formations with multiple problematic layers and complex pressure systems, making accurate predictions challenging. As depth increases, drilling efficiency is highlighted as a major issue. Furthermore, the adaptability of drilling equipment and tools for Class II high-temperature and high-pressure conditions (pressure up to 137.9 MPa and temperature up to 204°C) is insufficient, and Class III high-temperature and high-pressure (pressure up to 206.8 MPa and temperature up to 260°C) drilling and completion technologies are virtually non-existent. Additionally, deep abrasive formations pose challenges in terms of low rock-breaking efficiency and slow drilling speed. Low alteration degree of deep reservoirs and conflicts between multiple pressure systems and wellbore structural hierarchies further add to the difficulties. With the increasing complexity of oil and gas exploration and development targets and the continuous increase in well depths, high-temperature and high-pressure conditions have become more prevalent, bringing new technical challenges (such as large temperature differentials and pressure differentials). As a result, drilling processes become more complex, leading to high accident rates and drilling costs. Consequently, higher requirements will be placed on deep and ultra-deep well drilling[6].

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2.2. Design and Optimization of New Drilling Bits for Ultra-deep Wells

For a long time, deep and ultra-deep well drilling has been characterized by low mechanical drilling speed, high consumption of drill bits, limited footage per individual drill bit, and frequent tripping operations. On one hand, the substantial consolidation effect in the formation results in increased rock strength and reduced fragmentation. On the other hand, the energy of drill bit breaking formations is diminished due to well depth and wear, leading to an inevitable decline in mechanical drilling speed. However, well depths are objective and exist, necessitating the improvement of drill bit energy for breaking formations to enhance mechanical drilling speed.

2.3. Domestic High-efficiency Drilling and Speeding-up Technologies for Ultra-deep Wells

For a long time, deep and ultra-deep well drilling has been characterized by low mechanical drilling speed, high consumption of drill bits, limited footage per individual drill bit, and frequent tripping operations. On one hand, the substantial consolidation effect in the formation results in increased rock strength and reduced fragmentation. On the other hand, the energy of drill bit breaking formations is diminished due to well depth and wear, leading to an inevitable decline in mechanical drilling speed. However, well depths are objective and exist, necessitating the improvement of drill bit energy for breaking formations to enhance mechanical drilling speed[7-8].

3. Advanced Well Cementing Techniques and Supporting Technologies for Ultra-deep Wells, both Domestically and Internationally

3.1. Current Status and Challenges of Ultra-deep Well Cementing Technology

3.1.1. Current Status

At present, the research status of well cementing technology in China can be summarized in several aspects[9-10]:

(1) The circulation processing time of drilling fluids before cementing can be determined using the circulating volume efficiency method, and it can also be used to judge whether the downhole drilling fluids are fully circulated.

(2) Low return speed cementing technology has become more mature. For some deep and ultra-deep wells, turbulent cementing is difficult to achieve due to external factors. Therefore, low return speed cementing technology can be used to improve the cementing effect in deep and ultra-deep wells.

(3) With the continuous in-depth research on gas migration mechanism, the mechanism of cement slurry lost circulation and gas migration has been clarified. Factors affecting gas migration have also been summarized. Based on this, comprehensive anti-gas migration technology measures have been widely applied.

(4) Research on cementing technology for deep and ultra-deep wells has received attention, and through the continuous efforts of researchers, the application level of cementing technology for deep and ultra-deep wells in China has been improving year by year.

3.1.2. Technical Challenges

Due to the complexity of deep wellbore conditions, multiple pressure systems, longer wellbore sections, smaller annular clearances, and the high temperature and high density of deep well sections, the quality of casing cementing in ultra-deep wells is poor, and it is difficult to meet the long-term well integrity requirements. The main technical challenges are as follows[11]:

(1) Multiple pressure layers exist in the same openhole section, and there is a large difference in pressure coefficient.

(2) High bottom circulation temperature and sensitivity to fluctuations.
(3) Small annular clearance in the lower section.
(4) The creep of salt formation poses challenges to cementing.
(5) High requirements for cement slurry density.
(6) Cement slurry is severely contaminated by drilling fluids.

3.2. Typical Ultra-deep Well Cementing Technologies at Home and Abroad

(1) Isolation Fluid Leak Prevention and Plugging Technique

By adding leak plugging materials to the isolation fluid, temporary plugging can be achieved during cementing to reduce the risk of wellbore leakage during cementing operations, facilitating cement slurry to return to the designed well depth. In the tail casing cementing of Well Area 3 in Shunbei Oil and Gas Field, where multiple leakage zones are widespread, it is challenging to achieve satisfactory leak prevention and plugging effects with conventional drilling fluid plugging or low-density cement slurries. Therefore, targeted leak prevention techniques are necessary. By mixing polypropylene fibers with lengths of 0.5 mm, 1.0 mm, and 1.5 mm and adding them to the isolation fluid at a dosage of 0.15% to 0.20%, the isolation fluid gains a certain leak prevention and plugging capability. The mechanism behind this is that when the isolation fluid passes through the leakage zone, it filters through the leakage zone under the action of pressure difference, resulting in increased viscosity of the isolation fluid. At the same time, the fibers bridge in the leakage zone, forming a network structure. The weighting agent in the isolation fluid adheres to the fiber network, forming a dense filter cake, which rapidly reduces the permeability of the filter cake and prevents leakage[12].

(2) "Positive Displacement Squeeze" Cementing Technique

The "positive displacement squeeze" cementing technique is a common method to address cementing losses and is suitable for severe losses or losses in return in various conditions. It can be divided into one-time squeezing, two-time squeezing, and multiple-time squeezing. Before construction, the choice of squeezing method should be determined based on the difference between the loss rate, cement slurry density, and drilling fluid density. The key to the "positive displacement squeeze" technique is to accurately identify the leakage zone and have a clear understanding of it. When designing the amount of cement slurry to be positively displaced, it should be ensured that the cement slurry reaches the position of the leakage zone without sealing the leakage zone. When designing the amount of cement slurry to be squeezed, it should be ensured that it is injected into the leakage zone, thereby ensuring the complete filling of the entire annular space and not sealing the wellbore section. If severe leakage exists and squeezing pressure cannot be achieved, multiple squeezes can be applied. Alternatively, after waiting for solidification, the squeezing scheme can be determined based on the actual rebound height of cement slurry detected by amplitude measurement[13].

3.3. Ultra-deep Well Cement Slurry Systems

3.3.1. High-temperature Resistant and Corrosion-resistant Cement Slurry System

Highly acidic gas reservoirs are corrosive to cementing annulus, and gas migration can cause significant damage to the surrounding ecological environment. A typical example is the Yuanba Gas Field, where the main production layers are the Permian Changxing Formation reef and shoal reservoirs, with depths generally ranging from 6500m to 7500m and bottomhole temperatures close to 160°C. The natural gas in this field contains up to 20% H2S and over 12% CO2. To meet the cementing requirements under these specific geological conditions, a high-temperature resistant, corrosion-resistant, and gas migration preventive cement slurry system has been successfully developed. It addresses deep well high-pressure gas migration prevention and high-temperature resistance in the unique geological conditions of the Yuanba Block, as well as the corrosion of cement stone in highly acidic environments. This system

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ensures cementing quality to meet the needs of later production and provides valuable reference for the development and application of cementing technology for other marine ultra-deep wells.

3.3.2. High-pressure Low-density Cement Slurry System

Low-density cement slurry should meet the following requirements:

High pressure-bearing capacity: Under downhole liquid column pressure, the density reducing agents should remain essentially unbroken, and the increase in cement slurry density should be ≤0.03 kg/L.

72-hour compressive strength of cement stone should be ≥14 MPa, and the strength of cement stone at high temperatures should be stable.

It should have good settlement stability, with a density difference of the cement slurry column above and below ≤0.03 kg/L.

The thickening time should be adjustable, and the thickening curve should be stable.

According to the industry standard "Cementing Design Code for Oil and Gas Wells" (SY/T5480—2016), to improve displacement efficiency, the entry slurries should have a certain density difference. Usually, the density of the cement slurry should be 0.24 kg/L higher than the density of the drilling fluid. However, in the leakage pressure equivalent density in the Shunbei Oil and Gas Field, it ranges from 1.35 kg/L to 1.40 kg/L, which is very close to the density of the drilling fluid, making it challenging to meet the requirements of SY/T5480-2016. To reduce the risk of losses during cementing, the drilling fluid is typically used to pre-pressurize and plug the well, increasing the equivalent density of the formation pressure to about 1.40 kg/L. Based on the formation pressure capacity, the density of the isolation fluid is designed to be 1.40 kg/L to 1.45 kg/L, and the density of the low-density cement slurry is designed to be 1.45 kg/L to 1.50 kg/L. This way, there is a density difference between the drilling fluid, isolation fluid, and cement slurry, allowing for positive density difference displacement. Additionally, the flushing fluid is typically designed with a density of 1.03 kg/L during cementing to reduce the static column pressure of the isolation fluid and cement slurry, ensuring that the annular liquid column pressure is approximately equal to the leakage pressure, thereby reducing the risk of losses during cement injection and waiting for thickening[14].

3.3.3. High-temperature Multifunctional Anti-gas Migration Cement Slurry System

According to the Stokes settling velocity formula and particle size distribution principle, under the premise of determining the weighting material, reducing particle size, increasing the viscosity of the dispersing medium, and the liquid suspension density can increase the slurry stability. Fluid loss reducers usually increase the viscosity of cement slurry. External materials such as silica sand and ultrafine materials (microsilica, latex, etc., with different particle sizes) can not only increase the solid phase packing density and fill voids but also improve high-temperature thixotropy, solid-phase particle structure force, and strength stability, which are beneficial to improving the sedimentation stability of the cement slurry system. Fluid loss reducers JS-1 and JS-2 have good fluid loss reduction effects and sedimentation stability at high temperatures. However, with the increase in cement slurry system density and experimental temperature, JS-1 shows better stability at lower dosages, but increasing the dosage of fluid loss reducers alone cannot meet the high-temperature sedimentation stability requirements[15].

4. Summary and Outlook

4.1. Ultra-deep Well Efficient Drilling and Speeding Up Technologies

Through research and application of ultra-deep well efficient drilling and speeding up technologies, a number of new drilling technologies, processes, and tools have been developed,

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significantly improving drilling speeds and achieving notable progress in ultra-deep well drilling technology in oil and gas fields like the Tarim Oilfield and Southwest Oil and Gas Fields. As oil and gas exploration and development continue to move into deeper layers, key oil and gas storage and production regions like the Sichuan-Chongqing Gas Zone and the Kuqa Foreland Basin in the Tarim Oilfield still face many technical challenges and cost pressures due to low oil prices. It is recommended to focus on key areas such as new technologies and methods for speeding up complex deep well drilling, new equipment and tools for automation and high-efficiency drilling in deep and ultra-deep wells, and integrated testing and promotion of drilling technologies. This will help achieve an overall international advanced level in deep/ultra-deep well drilling technology.

(1) Optimization of Wellbore Structure

By analyzing drilling data and studying formation three-pressure profiles, optimizing the position of necessary casing points can be done to shorten the length of large-diameter well sections and effectively separate high and low-pressure layers, ultimately achieving the goal of improving drilling speed and reducing drilling complexity.

(2) Design and Selection of Speeding Up Tools like Impactors and Drill Bits

Further research on multi-dimensional impactors and other speeding up tools should be conducted, and field tests of personalized drill bit matching should be carried out. In addition, long-life high-torque screws, rotary percussion tools, turbine drilling tools, and other speeding up tools still have gaps in high-temperature resistance, corrosion resistance, and long life compared to foreign counterparts. Reliability, adaptability to formations, and other aspects need further research based on formation characteristics. The upper large-diameter wellbore and difficult drilling formations encounter challenges during drilling, such as severe drill tool vibrations and stick-slip, which can lead to tool damage. To address this, underground drilling column abnormal vibration monitoring should be conducted, and corresponding vibration reduction tools should be developed to achieve safe and rapid drilling.

(3) Conducting Upward Onshore Formation Air Drilling

Traditional air drilling technology has shown significant speeding up effects, but it is difficult to implement in complex formations with poor wall stability and severe water seepage, severely limiting the application of air drilling. However, reverse circulation air drilling, where the gas is discharged and sand returned through the inner tube of the double-walled drill string, reduces the interaction between high-speed gas flow and the wellbore wall, providing significant advantages in handling complex formations mentioned above. Furthermore, it requires lower gas demand than traditional air drilling, effectively expanding the application of air drilling.

4.2. Cementing Technology and Supporting Techniques

Cementing challenges vary across different regions. Taking Shunbei Block 1 as an example, the cementing challenges mainly include crack development, low formation pressure-bearing capacity, and potential for leakage; long primary cementing sections that are prone to pressure leakage; and small annular clearances and high circulating friction. The challenges for wellbore cementing in Chongqing Deep Well 1 include high gas migration risk and difficulties in preventing gas migration, adjustments in high-temperature and high-density cement slurry performance, and difficulties in ensuring efficient displacement.

To address the challenges in high-temperature, high-pressure, high-sulfur, narrow safety density windows, and long cementing sections in deep and ultra-deep wells, continuous research and development efforts are required:

Conduct research on cement slurry systems and high-performance cementing materials that can withstand temperatures above 200°C.

Develop temperature-spectrum oil well cement additives to address problems related to long cementing sections and large temperature differences, achieving temperature differences greater than 70°C in cement slurry systems.

Develop high-temperature and high-pressure resistant, highly reliable tailpipe hangers, and other cementing tools.

Research and develop cement slurries that are resistant to high temperatures, corrosion, and gas migration, enhancing the structural integrity and long-term mechanical stability of cement stone at high temperatures.

Address the narrow density window and small annular clearances by developing large-volume displacement cementing equipment and supporting processes to improve the efficiency and quality of cement displacement.

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