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Research status and development trend of simulation experiments on the formation of underground crack sealing layer

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Abstract:
This paper provides an overview of the issue of drilling fluid leakage and strategies to address it. The focus is on preventing borehole wall collapse and ensuring well wall stability in complex geological environments through the use of advanced plugging technologies and materials. The research analyses drilling and plugging materials suitable for high-temperature formations, adaptive leakage prevention and plugging technologies, and innovative applications of micro and nano technologies to enhance the effectiveness of drilling fluid plugging. It also examines the unique effects of different plugging technologies in forming a plugging layer. The research results suggest that numerical simulation is crucial in studying oilfield fracture plugging technology. The researchers used computational fluid dynamics (CFD) and discrete element method (CFD-DEM) to gain insights into the microscopic mechanisms of fracture plugging. This included the formation of particle bridges and the construction of force chain networks. Numerical simulations were conducted to investigate the impact of various factors, such as particle size distribution and elastic modulus of plugging materials, on the plugging effect. This research offers theoretical guidance for selecting plugging materials and optimizing formulations, resulting in significant improvements in plugging efficiency and durability. Therefore, this research has made a significant contribution to the advancement of plugging technology. Experimental simulation is crucial for verifying numerical simulations. Core tests and material performance tests were conducted under high temperature and high pressure environments to confirm predicted results and field test material performance in actual application environments. The material formulation was optimised to suit different crack widths and operating environments. Field tests not only helped with this optimisation but also revealed new possible problems and facilitated the development of solutions. The combination of numerical and experimental simulations provides strong support for the advancement of oilfield fracture plugging technology, greatly enhancing its reliability and effectiveness.
Keywords: *plugging technology, drilling fluids, plug layers, plugging particles, wellbore, plugging agents*

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I. Introduction

Well leakage is a frequent and challenging problem in drilling, which involves the loss of drilling fluids to pore spaces, fractures, and cavities in the formation due to multiple differential pressures. This phenomenon can cause significant loss of drilling fluids and extend drilling cycle time unnecessarily. It can also lead to serious and complex risks such as well caving, blowouts, and stuck drilling. In extreme cases, it may even result in borehole abandonment if not handled properly [1][2]. Statistics show that approximately 26% of oil and gas wells worldwide experience well leakage issues, resulting in an annual expenditure of up to US$2 billion for plugging the leaks. The problem of well leakage has become increasingly prominent with the expansion of oil and gas exploration and development into more challenging areas, such as deep, ultra-deep, and deep water in the ocean, indicating a more serious situation. In response to this challenge, researchers have developed several rules for optimising the size of plugging particles in porous and fractured formations. The goal is to improve plugging efficiency by adjusting the size of the particles to match the size of the pores or fractures in the formation, resulting in an optimal distribution of particle sizes. However, the field still faces several challenges, including an unclear formation mechanism of the plugging layer, limited pressure-bearing capacity, and a low success rate of one-time plugging. This is especially critical when dealing with fracture leakage, as the physical stability of the plugging layer may be affected by factors such as wellbore pressure fluctuations and temperature changes, leading to mechanical instability that could negatively impact the plugging effect. The aim of this paper is to summarise numerical and experimental simulations on the formation of underground fracture plugging layers, discuss and summarise the current scientific research status and development trends of plugging layer formation, and provide strong theoretical and technical support for effectively responding to the problem of fracture stratum leakage and ensuring the safety and efficiency of drilling operations. The article addresses the issues of unclear formation mechanisms and insufficient pressure-bearing capacity of the plugging layer. It also provides direction for improving the success rate of one-time leakage plugging.

II. Numerical simulation

Numerical simulation involves the use of mathematical models and computer techniques to replicate real-world processes. This allows researchers to predict future behaviour, optimise parameters, and perform safety analyses efficiently, reducing the need for physical experiments and saving time and resources. The author has integrated CFD-DEM techniques.

Xu Chengyuan et al utilised a coupled computational fluid dynamics and discrete element method (CFD-DEM) to conduct advanced simulations of the fracture sealing process. The team discovered that particle bridging effects and force chain networks at the microscopic level are the primary factors that determine the macroscopic strength of the seal. By using new materials with optimised sealing and delayed release properties, as well as careful formulation selection, it is possible to significantly improve the efficiency and strength of fracture sealing. This can also enhance the ability to control fluid loss in deep fractured reservoirs. Using CFD-DEM technology, Bao Dan developed a three-dimensional fluid-solid coupling analysis model to simulate the behaviour of plugging particles in fractures. The effects of particle size, concentration, and surface friction coefficient on plugging efficiency were investigated. The study demonstrates that using plugging materials with different particle sizes can quickly construct a tighter sealing layer [3][5][7]. Increasing the modulus of elasticity, concentration, and friction coefficient of the plugging materials can enhance the sealing effect. Optimized plugging materials can efficiently build up, fill, and seal beam bridges within the cracks, forming a compact plugging layer with high loading capacity [3-8]. Higher stiffness bridging materials can construct a particle force chain network structure with stronger pressure-bearing capacity to enhance the load-bearing capacity of the sealing layer. It is important to note that this statement is objective and free from any biased or figurative language. Reasonable combinations of particle sizes and the use of organic fibre materials with large aspect ratios can further strengthen the blocking effect against the penetration of drilling fluids and enhance the shear strength of the sealing layer. This, in turn, increases its pressure-bearing capacity. After synthesising the research results and analysing the mechanism and key factors influencing fracture tight pressure sealing, Tyrannosaurus proposed four major strategies to strengthen the technology. The objectives of this process are: 1) to maintain stable suspension of the plugging fluid, 2) to improve the adaptive sealing ability of the plugging material to the formation cracks, 3) to optimize the characteristics of the plugging material, and 4) to enhance the synergistic sealing effect between different plugging materials.

III. Experimental simulation

Experimental simulation directly replicates phenomena through physical methods, providing a basis for verifying numerical simulations, revealing details that numerical simulations may not accurately capture, and intuitively demonstrating complex processes. The text summarises research experiments on core plugging performance evaluation, factors influencing well wall stability by analysing additive type and concentration parameters, and plugging material performance under high temperature conditions and their development.

3.1 Research experiments on the evaluation of core plugging performance

In their research on adaptive leakage prevention and plugging drilling fluid technology, Wang Zaiming et al. [9][10] investigated... The study verified the effectiveness of adaptive leakage prevention and plugging drilling fluid in leaky formations with varying pore size distributions through man-made core sealing experiments, indoor evaluations, and on-site applications in the Liaohe Oilfield. The sealing rate was over 90%, with a sealing zone pressure strength higher than 9 MPa, a sealing layer thickness less than 1 mm, and a permeability recovery rate of over 90% after slicing. The Liaohe oilfield application demonstrates that the adaptive leakage prevention and plugging drilling fluid has a success rate of 91.2%, while the one-time plugging success rate is 83.3%. This technology effectively improves the pressure-bearing capacity of the formation and prevents and plugs leaks, as shown by the analysis of specific drilling cases. Wang Pan analysed the retention behaviour of suspended particles [11][12] in water in porous media and their influence on water injection pressure using core experiments. The study shows how the water injection pressure adjusts with the physical properties of suspended particles, such as particle size and concentration, injection rate, and the porosity, permeability, and length of the medium. The experiments showed that injection pressure undergoes a dynamic process, stabilising, increasing, and then stabilising again. Larger particle sizes contribute to effectively sealing the porous medium and the sealing rate. At lower concentrations, the concentration mainly affects the rate of pressure rise rather than the peak value. An increase in injection rate accelerates pressure rise by increasing initial and maximum injection pressures. Lower porosities and permeabilities promote particle retention, regulating injection pressure. The length of the medium directly determines the initial value of injection pressure and the time required to reach stabilization. The optimal medium length was found to be 8 cm. These findings are significant for optimizing the injection process of fluids in porous media, particularly in improving the blocking efficiency and controlling the injection pressure.

3.2 Type and concentration of additives to influence the well wall

During the experiment, the additives' type and concentration were carefully adjusted to enhance the well wall's stability while drilling and to minimise drilling risks. Yong Qilong and their research team conducted an experimental comparison between high-temperature and high-density drilling fluid formulations using ordinary barite and ultrafine barite [13]. They found that while ultrafine barite improved the viscosity and shear force of the drilling fluid, enhancing rheology and settlement stability, it may also negatively impact drilling efficiency and well-wall stability. Therefore, it is necessary to regulate the drilling fluid's performance through dispersants to achieve a balance. Zhang Ting et al. (year) investigated the effects of adding nanomaterials, such as nano-silica [14], to drilling fluids on blocking ability and the risk of hydrological swelling of mud shale. The results showed that nano-silica can effectively construct a semi-permeable membrane blocking layer, reducing the risk of hydrological swelling. Additionally, it regulates the fluid's activity, reducing fluid exchange between drilling fluids and formations, thereby protecting the stability of the well wall. Similarly, Qu Yuanzhi's team conducted research on a new water-based drilling fluid that utilises nano-membrane structure technology[15]. Corresponding experiments showed that nano-silica can form a low-permeability blocking membrane, effectively inhibiting the hydration reaction of the core. This significantly improves the hydration resistance of the drilling fluid and reduces the swelling of the mud shale. As a result, it plays an important role in protecting the stability of the wall and preventing complex subsurface problems during the drilling process.

3.3 Research experiment on the performance of plugging materials under high-temperature conditions

In the research of high temperature plugging materials, it involves different types of organic plants and polymers, inorganic minerals, new high temperature resistant bridging and fibre plugging materials, etc. Especially in the optimization of particle size distribution and concentration ratio at depth, five teams, including Zhengqiang Xiong, Zhiming Chen, Xiaoming Zhao, Xiaobo Wu and Ganjie Li, have carried out experimental optimization of the particle size distribution and concentration for different types of high temperature resistant plugging materials [16-20]. Xiong Zhengqiang and other researchers thoroughly evaluated the aging effects of organic plants and polymers, inorganic minerals, new high temperature resistant rigid bridging plugging material (SDHTP-1) and high temperature resistant fibre plugging material (SDHTF-1) in high temperature environment. The resultant anti-temperature dense pressure-bearing plugging working fluid formulation can quickly form a plugging layer with a pressure-bearing capacity of more than 10MPa, showing good stability of sedimentation and high acid solubility. It provides a feasible solution for solving the technical problems of plugging in drilling wells in high-temperature formations or reservoirs. Chen's research involves organic composites and polymers, inorganic high-temperature stabilised mineral-based materials, and two novel materials: high-temperature reinforced bridging plugging material (HTRBP-1) and high-temperature creep-resistant fibre plugging material (HTACF-1). These studies have led to the development of a variety of high-temperature and high-pressure resistant sealing fluids for different formation fracture widths, which can rapidly form a strong pressure-bearing blocking layer under extreme conditions, effectively solving the challenge of plugging wells drilled in high-temperature formations. Zhao and his research team developed new high-temperature resistant rigid bridging and high-temperature stable fibre-reinforced plugging materials (HTRSP-X and HTSFP-X, respectively). By precisely adjusting the formulas, they developed a variety of high-temperature and high-pressure resistant sealing working fluids for different crack widths. These new formulas can quickly form a blocking layer with strong pressure-bearing capacity and good stability under high-temperature conditions, which effectively solves the leakage plugging problem in high-temperature stratigraphic drilling. Li Ganjie and his team conducted comprehensive tests and evaluations of their performance under high-temperature conditions by selecting a series of materials, including organic polymer materials, new polymer-based materials, inorganic high-temperature-resistant mineral-based materials, as well as independently researched and developed new high-temperature-resistant reinforced bridging plugging materials (HTBRP-1) and high-temperature stabilised fibre-reinforced plugging materials (HTSFP-1). Special attention was paid to the high-temperature aging effect of the materials and the synergistic effect between different materials. After continuous experimental optimisation, a series of formulations of high-temperature and high-pressure resistant sealing working fluids suitable for different formation crack widths have been successfully developed. These formulations can quickly form a sealing layer with high pressure-bearing capacity under high temperature conditions, with pressure-bearing capacity far exceeding 10MPa, showing excellent settlement stability and high alkali solubility.

Wu Xiaobo and his team conducted precise experiments to optimize the particle size and concentration of various high-temperature-resistant plugging materials to address technical problems encountered during the process of drilling wells in high-temperature formations. The experiments were based on the characteristics of the formations. The organic polymer materials, new polymers, inorganic mineral materials resistant to high temperatures, new rigid bridging plugging materials (HTARP-1), and high-temperature stabilized fiber-reinforced plugging materials (HTSFP-2) were evaluated for their aging effect and performance. This scientific research has resulted in the development of several formulations of high-temperature-resistant dense pressure-bearing plugging working fluids suitable for different formation crack widths. These formulations can rapidly form a plugging layer with a pressure-bearing capacity of over 15MPa under high-temperature conditions, providing a stable and reliable technical guarantee for drilling operations in high-temperature formations.

IV. Development trend

Current research is focused on three main areas: improving the efficiency of plugging, enhancing the pressure-bearing capacity of the plugging layer, and reinforcing the stability of the plugging material. Researchers have optimised particle size gradation and concentration using the coupled simulation technology of Computational Fluid Dynamics and Discrete Element Method (CFD-DEM). They have also conducted exhaustive tests on various types of plugging materials, including organic polymer materials, inorganic high-temperature-resistant mineral materials, and new types of high-temperature-resistant and rigid bridging plugging materials. These efforts have improved the formation efficiency and stability of the plugging layer, as well as its pressure-bearing capacity. Additionally, they have shown great potential for drilling wells in high-temperature formations. These results offer strong theoretical and experimental evidence for the quick creation of plugging layers that can withstand high pressure in extreme environments.

Looking to the future, research may focus on the following areas: The task at hand involves two main objectives. Firstly, the development of new plugging materials with improved performance, particularly in high-temperature stability and pressure resistance. Additionally, customised materials that can be adapted to different formation environments are required. Secondly, it is necessary to combine the characteristics of different formations and the specific requirements of the drilling environment to explore more efficient plugging solutions and technologies. This will ensure precise matching between material selection and the plugging process. Thirdly, the aim is to investigate more efficient plugging solutions and technologies, and to achieve precise matching between material selection. Additionally, CFD-DEM and other cutting-edge numerical simulation technologies will be used to explore the micro-mechanism of plugging layer formation. This will provide more accurate guidance for the selection of plugging materials and optimization of plugging technology. The fourth consideration is the suspension stability of plugging materials, the adaptive plugging ability of formation cracks, the optimization of material properties, and the synergistic effect of multiple types of plugging materials. The aim is to improve the all-round blocking efficiency and mechanical stability of the blocking layer in all aspects.

V. Conclusion and Recommendation

This paper reviews the problem of drilling fluid leakage and strategies to address it, particularly in complex geological environments. It discusses the use of advanced plugging technology and materials to prevent hole wall collapse and ensure well wall stability. Through extensive research on innovative applications of drilling plugging materials for high-temperature formations, adaptive anti-leakage plugging technology, and micro-nanotechnology to enhance the effectiveness of drilling fluid plugging, we have drawn important conclusions and feasibility suggestions.

One key solution to the problem of drilling fluid leakage is the continuous innovation and development of plugging technology. The development and application of new plugging materials have significantly improved the efficiency and stability of the plugging layer, particularly in the drilling of high-temperature formations. These materials exhibit excellent high-temperature resistance and maintain a stable plugging effect even in extreme environments, providing a reliable solution for drilling operations in complex geological environments.

Another numerical simulation is crucial in researching oilfield fracture plugging technology. By combining Computational Fluid Dynamics (CFD) and Discrete Element Method (CFD-DEM), a deeper understanding of the microscopic mechanism of fracture plugging can be gained, leading to more accurate predictions and simulations of the plugging layer formation process. This section provides theoretical guidance for selecting and optimizing plugging materials, improving plugging efficiency and durability.

Additionally, it is important to continue strengthening research and development efforts in plugging technology. This includes researching and developing new blocking materials with excellent performance and strong adaptability to improve blocking efficiency and stability in complex geological environments. Simultaneously, research on adaptive leakage prevention and plugging technology should be strengthened to better adapt to various geological conditions and drilling environments.

Additionally, numerical simulation should be utilized to its full potential in plugging technology research. By continuously improving the numerical model and method, simulation accuracy and efficiency can be enhanced. This will provide a more precise theoretical basis for selecting plugging materials, optimizing formulas, and determining process parameters.

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