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Research Status and Prospects of Leakage Sealing in Fractured-Lined Strata

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Abstract

As an important part of unconventional oil and gas resources, deep oil and gas has attracted wide attention in China 's energy field in recent years. Deep oil and gas resources are mostly in complex strata, complex pressure systems and other high-difficulty areas. The drilling strata are more complex, and multi-scale fractures or even karst caves are generally developed. The engineering environment is harsh and the drilling engineering is complex. When drilling into broken and fractured formations, the problem of leakage is particularly prominent. The lost circulation in fractured-vuggy formations has become one of the common and difficult downhole complex accidents in the drilling process. In this paper, the characterization of leakage channels, plugging mechanism, numerical simulation of plugging materials and design criteria of plugging materials in fractured-vuggy formations are described, and the shortcomings are analyzed and the future research directions are prospected.

Keywords

Fractured Porous Strata, Leakage Channel, Leakage Sealing Mechanism, Numerical Simulation, Leakage Sealing Material.

1. Introduction

China 's oil and gas consumption demand has increased year by year. According to statistics, in 2023, China 's external dependence on crude oil reached 72.99 %, while the external dependence on natural gas was 40.14 %, which undoubtedly poses a serious threat to the country 's energy security. Conventional oil and gas resources can no longer meet the growing energy demand. The status of unconventional oil and gas resources is becoming more and more important, and it has become an important part of the growth of oil and gas resources exploitation[1]. As an important part of unconventional oil and gas resources, deep oil and gas has attracted wide attention in China 's energy field in recent years. Deep oil and gas resources are mostly in complex strata, complex pressure systems and other high-difficulty areas. The drilling strata are more complex, and multi-scale fractures or even karst caves are generally developed. The engineering environment is harsh and the drilling engineering is complex. When drilling into broken and fractured formations, the problem of leakage is particularly prominent[2-5]. The lost circulation in fractured-vuggy formations has become one of the most common and difficult downhole complex accidents in the drilling process[6]. Because of its natural fractures and karst caves, the fractured-vuggy strata form a complex pore structure, which seriously affects the safety and economy of production operations.

2. Characteristics of Fractured-Vuggy Strata

Fractured-vuggy reservoirs are mainly composed of fractures, pores and caves, which play an important role in oil and gas exploration. From micron-scale fractures to meter-scale karst caves, the spatial structures of different scales are intertwined, which makes the fractured-vuggy strata present multi-level complexity on the scale. The fracture network of the formation

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forms a complex three-dimensional geometric structure. These fractures are not only the main transport channels of fluid, but also connected with the underground karst cave system to promote the efficient transmission of fluid. As a large pore space, karst cave can not only increase reservoir capacity, but also an important place for underground fluid enrichment. The spatial inhomogeneity is manifested in the complex diversity of the size, direction and connectivity of pores and fractures. These characteristics bring great challenges to the plugging, which need to be further studied.

3. Research Status at Home and Abroad

3.1. Research Status of Plugging Mechanism in Fractured-Vuggy Formation

Eliminating leakage and ensuring drilling safety are the goals of plugging work. Scholars at home and abroad have carried out research on plugging the leakage layer and strengthening the wellbore, and formed a series of formation pressure-bearing capacity strengthening theories. There are mainly stress cage theory, theory of improving fracture closure stress, theory of improving fracture extension stress, theory of wellbore strengthening by chemical method and so on.

(1) ''Stress cage'' theory

The stress cage theory was proposed by Aston in 2004 [7]. The theory points out that after the plugging material enters the crack with the drilling fluid, a plugging layer is formed at the entrance. As the plugging material accumulates, the permeability of the plugging layer gradually decreases, thereby preventing the pressure from diffusing to the crack tip. At the same time, the accumulation of plugging materials can support cracks, increase the stress around the well, form a stress cage, prevent cracks from opening or extending, and improve the pressure bearing capacity of the wellbore [8]. Whitfill, Sweatman, Wang et al. [9-13] improved the theory of wellbore strengthening through laboratory experiments, numerical simulation and field application research. Through the stress cage effect, the wellbore circumferential formation pressure can be effectively increased and the wellbore can be strengthened. This theory is mainly applicable to the formation with good permeability or small fracture leakage, and has certain requirements for the compressive strength, hardness, type and gradation of plugging materials.

(2) Improve the theory of crack closure stress

The theory is similar to the ' stress cage ' theory. To a certain extent, it is through the plugging body to support the fracture and compress the circumferential formation. The difference is that the plugging body is formed by the rapid loss of water accumulation of the plugging material inside the fracture, which does not rely on the bridging effect inside the fracture, thus reducing the requirement for the strength of the granular material to a certain extent. Dupriest et al. [14] put forward the theory of " fracture closure stress, " that is, by widening the cracks formed on the wellbore to increase the compressive stress of the rock around the cracks, and then isolating the wellbore and the pressure conduction at the crack tip through the plugging material, thus effectively inhibiting the reopening and extension of the cracks. This theory is mainly applicable to the formation with good permeability or micro-fractured leakage. Compared with the ' stress cage ' theory, the compressive strength, type and gradation requirements of the plugging material are also lower.

(3) The theory of improving crack extension pressure

Based on the theoretical analysis and numerical simulation of fracture mechanics, Feng et al. [15] believed that increasing the fracture extension pressure can effectively strengthen the wellbore. Zhao et al. [16] used numerical simulation method to study the mechanism of wellbore strengthening from two aspects of wellbore stress strengthening and anti-fracture strengthening. It is considered that the fracture extension pressure is significantly increased after the fracture is effectively blocked. This theory has a lower requirement for the permeability of the formation and a wider application range. It can be applied to porous and micro-fractured leakage formations, but it has higher requirements for the type and gradation of plugging materials.

(4) Blocking crack tip theory

The DEA-13 experiment carried out in the 1980 s laid the foundation for the theory of blocking crack tip by studying the difference in fracturing behavior between oil-based mud and water-based mud [17-19]. Van Oort et al.compared and analyzed the ' stress cage ' and the theory of blocking crack tip through experiments, and concluded that both theories can be attributed to the principle of wellbore circumferential stress increase. However, the difference is that the fracture hypothesis in the ' stress cage ' theory is not realistic and the field application is poor, while the theory of blocking the crack tip needs to be realized in the permeable formation [20].

(5) Chemically enhanced wellbore theory

The chemical treatment of lost circulation is to pump the plugging slurry containing special materials into the wellbore. After the plugging material enters the fracture, it undergoes physical and chemical reactions under the combined action of temperature, pressure and fluid environment to form a high-strength plugging structure. The wellbore pressure and the pressure in the fracture are communicated to achieve the goal of improving the pressure bearing capacity of the wellbore. Kang Yi Li et al. [21] put forward the theory of strong solid ring, and put forward the use of chemical materials to seal the leakage layer. Chemical materials will be affected by temperature and pressure in the leakage channel, and complex physical and chemical reactions will occur. Colloids are produced to improve the structural strength of the weak surface of the rock mass, isolate the pressure conduction of the wellbore and the formation, and improve the pressure bearing capacity of the formation.

3.2. Research Status of Numerical Simulation of Plugging in Fractured-Vuggy Formation

At present, most scholars have studied the plugging mechanism of plugging particles through experiments, but the experimental period is long and the experimental results are accidental. At the same time, every time an experiment is carried out, it is necessary to redesign the experimental scheme and reconfigure the plugging formula. It takes a lot of time, the experimental period is long, and a lot of manpower, material and financial resources are spent, but the ideal experimental results are not necessarily obtained. Most importantly, due to the limitation of plugging experiment, the mechanism of plugging fracture of plugging particle bridge cannot be explained from the microscopic point of view. The numerical simulation experiment method can solve these problems well, and simulate some experiments that cannot be satisfied by the actual conditions, which is convenient for analyzing the microscopic mechanism. At present, with the rise of computational fluid dynamics (CFD) and discrete element method (DEM), CFD-DEM coupling simulation technology has been widely used in the study of plugging. Wang et al. [22] studied the influence of particle parameters on fracture plugging performance by using DEM without considering the influence of fluid. Feng et al. [23] considered the influence of the roughness of the fracture surface, and used the CFD-DEM method to simulate the non-uniform bridging mode of the plugging material in the rough fracture.Feng et al. [24] considered the influence of parameters such as particle size, concentration, particle size distribution and fracture morphology of rigid plugging particles when studying the influence law of fracture leakage plugging efficiency, and revealed the plugging mechanism. Xu et al. [25] used CFD-DEM method to simulate the formation process of fracture sealing layer structure, and revealed the formation and evolution mechanism of fracture sealing layer structure. However, there are few studies on fractured-vuggy strata.

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3.3. Research Status of Plugging Materials in Fractured-Vuggy Formations

Plugging materials are the basis and key of plugging technology. There are many kinds of materials used for plugging at home and abroad. According to their mechanism of action, they can be divided into bridging plugging materials, high water loss plugging materials, curable materials, intelligent plugging materials, etc. [26].

The bridging plugging material is a composite plugging material formed by granular, fibrous, flake and other inert materials according to a certain mass ratio and particle size gradation. Commonly used bridging materials include walnut shell, calcium carbonate, fiber, mica sheet, etc. Amanullah [27] developed a series of bridging granular plugging materials ARC by using date palm kernel, and the sealing pressure bearing capacity of the fracture with a width of 2mm was more than 8MPa. Kang et al. [28] evaluated the plugging effect of different types of bridging materials, including rigid particles, elastic particles and fibers, on millimeter-scale fractures when they were used alone and in combination. The experimental results showed that the ''rigid + elastic + fiber'' composite bridging material had the best plugging effect on millimeter-scale fractures, and the maximum pressure-bearing plugging capacity for fractures with a fracture width of 2mm reached 13 MPa.

The principle of bridging plugging material is mechanical plugging, and the way to play its role can be subdivided into : ' stuck throat ' effect ; blocking and embedding effect ; hanging resistance ' bridge ' role ; the ' pulling ' effect in the filter cake ; infiltration ; expansion blocking effect. Bridge plugging has been widely used because of its convenient construction, safety and economy, accounting for more than half of the whole plugging treatment method, and the effect is ideal [29].

The bridging plugging material itself is a renewable resource and an environmentally friendly material. The advantages are low cost, simple operation, and less influence on the rheology of drilling fluid. However, the shortcomings of bridging materials are also very obvious. On the one hand, it is difficult to accurately measure the width of formation fractures. Choosing bridging materials in large and medium fractures and caves is easy to mismatch the material with the formation leakage channel, and it is not easy to form a plugging layer. On the other hand, the sealing layer of bridging materials in small and medium-sized fractures is easy to form a sealing door. Due to gravity settlement, fluid erosion and other reasons, it is not easy to stay and easy to re-leakage.

The high water loss plugging material is a plugging material made up of diatomite, percolation material and inert material in a certain proportion. After this kind of plugging material enters the formation fracture, it quickly loses water under the pressure difference between the formation pressure and the drilling fluid column pressure, and the solid phase component accumulates and thickens rapidly to form a film or filter cake to plug the fracture leakage channel. DiasealM plugging material and DSL plugging agent developed by Chevron Phillips are typical high water loss plugging materials. High water loss plugging materials are easy to use, quick to take effect and high success rate. They are suitable for plugging in permeable and micro-fractured formations with low leakage rate, but the plugging effect on fracture-cavity leakage needs to be further improved.

The polymer gel is plugged by the viscoelastic body of the three-dimensional cage structure formed by mutual crosslinking. This kind of gel has strong deformability and is not limited by the leakage channel. The field application of the polymer gel shows that the gelation time of the traditional gel plugging system is difficult to control, which increases the uncertainty and control difficulty for the gel plugging. Polymer gels need to have certain controllability. The general main strategies are to change the crosslinking environment, add delayed crosslinking agent, encapsulate crosslinking agent, control crosslinking by thixotropic conditions, control crosslinking reaction by shear action, and ion-induced crosslinking [30]. There are various

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types of polymer gels, and the representative one in China is the special gel ZND developed by Academician Luo Pingya based on structural fluid theory and supramolecular chemistry principle. The main design idea is that a gel is easier to enter the leakage layer, automatically stops the flow in the leakage layer, and fills the space of cracks and holes. It is difficult to mix with oil, gas and water, forming a slug that can cut off the internal fluid of the formation and the wellbore fluid. The slug has enough starting pressure to achieve the purpose of plugging. Therefore, the gel needs to have high viscosity and good shear thinning stress.

The curable material refers to the plugging material composed of a mixture of cement, slag, gypsum, lime, silicate, etc.and additives such as activators. Cement is a typical curable material. It can improve the plugging effect of cement by adding various cement slurry admixtures and improving the squeezing process. It has the characteristics of strong pressure bearing capacity and remarkable effect on dealing with serious leakage formation. The main plugging principle is : the cement slurry is pumped into the underground leakage layer for a certain time, and then it is thickened and solidified to form a solid body with high strength, which is cemented with the formation to achieve the purpose of plugging the leakage layer. The curable plugging material has high pressure sealing ability, easy control of curing time, low price, simple preparation and operation process, and is suitable for malignant leakage formations. However, the material is easily diluted by formation water, the curing strength after dilution is low, the curing time and rate are not easy to control, and the construction safety risk is high.

Intelligent plugging material is a relatively new plugging material. This material can respond to external environmental stimuli, can better adapt to environmental changes, and then can carry out plugging operations efficiently. There are various types of intelligent plugging materials, including intelligent shape memory materials, intelligent gel materials, intelligent membrane materials and intelligent bionic materials [31]. It has the advantages of good formation adaptability, high pressure strength, and can be effectively retained in the leakage channel, effectively avoiding the difficulty of grading of granular materials and the difficulty of controlling the gelation time of gel materials. However, the production cost of this material is high, the economy needs to be improved and the technology is not mature enough, which needs further exploration.

Table 1. Types and main mechanism of plugging materials

Type	Typical plugging materials	Main mechanism
Bridge class	Quartz sand, mica sheet, cotton fiber, etc	Inert material bridging, reinforcement, filling, blocking, etc
High water loss class	Fly ash, asbestos fiber, clay, etc	Rapid water loss, solid particles quickly gathered to block the leakage channel to form a plugging layer
Polymer gel class	Polyacrylamide gel, biological gel, polyvinyl alcohol gel, etc	Cross-linked gelling, winding or association of polymer chains with special functional groups
Curable class	Cement, silicate, slag, etc	Solidified to form a high-strength consolidation body, bonded to the ground
Smart Materials	Shape memory metal, memory polymer, intelligent gel, etc	The leakage is sealed by spontaneous physical and chemical reactions produced by environmental stimulation

3.4. Research Status of Design Method of Plugging Material in Fractured-Vuggy Formation

Through a lot of research by scholars at home and abroad, many design rules of plugging materials have been formed, mainly including : ''1/3 bridge'' rule, ''D50'' rule, ''D90'' rule, ''Ideal filling'' rule and so on.

The ''1/3 bridging'' rule was proposed by Abrams in 1977, which means that when the median particle size of the plugging material is equal to 1/3 of the pore size of the formation, effective plugging can be achieved to prevent the continuous loss of drilling fluid [32]. Based on the ''1/3 bridging'' rule, Luo Pingya et al.proposed the ''shielding temporary plugging'' plugging theory, that is, when the size of plugging particles is 1/2-2/3 of the pore size of the formation, a stable and dense plugging layer can be formed in the formation [33]. The ''D50'' rule and the ''D90'' rule are proposed based on the fractured formation. When the characteristic values of the plugging particles (D50, D90) are equal to the initial width of the fracture, the plugging effect is the best [34,35]. ''Ideal filling'' is the optimal selection standard of plugging materials based on the evaluation index of particle accumulation efficiency. The theory points out that when the cumulative volume percentage of plugging particles is proportional to its D1/2, the ideal filling of particles can be achieved and a good plugging effect can be obtained [36]. There are many design theories and calibration methods for the particle size of plugging materials, and the differences are large.

Because there are many design methods of plugging materials, and the differences are often large, the particle size gradation of plugging materials designed according to the ''1/3 bridge'' rule, ''D50'' rule and ''D90'' rule is quite different. At present, there are few theoretical studies on the particle size design of plugging materials for fractured-vuggy formations.

4. Conclusion and Prospect

With the expansion of oil and gas exploration and development to the fields of deep-ultra-deep and unconventional oil and gas resources, fractured-vuggy formations are one of the most common and difficult downhole complex accidents in the drilling process. At present, some progress has been made in plugging mechanism, plugging materials and design criteria of plugging materials, but the existing technologies have not effectively solved the problem of well leakage in fractured-vuggy formations. Only by clarifying the formation leakage channel, plugging mechanism and the characteristics of various types of plugging materials, and using suitable design criteria for plugging materials, can an effective plugging layer be constructed to effectively solve the leakage problem of drilling fluid, thus ensuring the smooth progress of oil and gas exploration operations. In the future, attention should be paid to improving the characterization and plugging mechanism of formation leakage channels, and the formation mechanism of plugging layers constructed by different types of plugging materials should be further studied. Break the technical barriers, realize the application of intelligent plugging materials in fractured-vuggy formations, and effectively deal with the problem of lost circulation, so as to meet the needs of complex formations, achieve ' efficient, safe and economical ' drilling, and accelerate the process of oil and gas exploration and development.

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