Drilling Fluid Loss and Lost Circulation Control Technology

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Lost circulation in fractured formation is the first major technical problem that restricts improvements in the quality and efficiency of oil and gas drilling engineering. Improving the success rate of one-time lost circulation control is an urgent demand to ensure “safe, efficient and economic” drilling in oilfields all over the world.

Keywords: fractured formation ; drilling fluid ; lost circulation control mechanism ; lost circulation material ; evaluation method

1. Introduction

Safe, economical and efficient drilling is the key premise to accelerating the process of deep and ultra-deep oil and gas exploration and development and to increasing oil and gas production [1]. However, deep and ultra-deep formation fractures are widely developed, and lost circulation frequently occurs in the drilling process. Thus, the success rate for one-time plugging and controlling lost circulation is low [2]. Existing domestic technology and the comprehensive introduction of foreign technology have not solved this, and it is the first major technical problem restricting the improvement in the quality and efficiency of oil and gas drilling engineering [3]. During the drilling process, lost circulation will lead to failure of the drilling rig, greatly increasing the non-productive time and resulting in significant economic losses [4]. According to statistics, the China National Petroleum Corporation (CNPC, Beijing, China), Sinopec, China National Offshore Oil Corporation (CNOOC, Beijing, China), Yanchang Petroleum, etc., experience direct economic losses of more than 10 billion yuan per year [1]. In recent years, the average annual loss time caused by lost circulation encountered by the China National Petroleum Corporation (CNPC) was over 4000 days, accounting for more than two-thirds of the total complex loss time of drilling accidents, with an annual direct economic loss of over 5 billion yuan [5]. Imperfections in the plugging material and drilling fluid technology is the fundamental cause of these economic losses, due to the lost circulation [6]. The development of a new plugging theory, new material and new technology is key to reducing the economic losses caused by lost circulation.

The establishment of an accurate and effective drilling fluid loss model is key to studying the drilling fluid loss mechanism in fractured formations [7][8]. According to the key data parameters of drilling fluid loss, the pressure plugging dynamic model of fractured formation can be established, and then a series of strengthening theories is formed to improve the pressure-bearing capacity of fractured formation, which provides a guaranteed selection of reasonable lost circulation materials and lost circulation control measures [9]. Lost circulation material is the basis for successful lost circulation control [10]. The effect of lost circulation material is determined by its applicability to loss conditions and types of drilling fluid [11]. Lost circulation characteristics determine the key performance parameters of lost circulation materials [12]. To clarify the characteristics and distribution of drilling fluid loss in fractured formation, the causes of drilling fluid loss in fractured formation need to be analyzed in depth, and the subsequent proposal of a new method to classify drilling fluid loss types is one way of preventing drilling fluid loss [13][14][15].

2. Lost Circulation Material and Performance of Fractured Formation

Lost circulation materials are the basis of, and key to achieving, successful plugging. Experts and scholars at home and abroad have developed a variety of lost circulation materials, such as bridging, high water loss, curable, liquid absorption and expansion, flexible gel, etc., and explored the properties of different types of lost circulation materials and their interaction mechanism with fractures.

2.1. Bridge Lost Circulation Materials and Properties

Bridge plugging is an the effective means of solving the problem of lost circulation in fractured formation. The plugging layer with a dense structure and high bearing capacity is formed by bridging, stacking and filling the fractures with different shapes and sizes of bridging lost circulation materials [16]. The bridge lost circulation material is composed of a granular, fibrous, sheet inert material according to a certain mass ratio and the particle size of the composite lost circulation material [17]. Commonly used bridging materials include walnut shell, calcium carbonate, fiber, mica, etc. However, conventional lost circulation materials are not compatible with the formation and cannot form high-strength plugging layers. Due to the influence of gravity settlement, erosion in the fracture and other factors, this is difficult to place in large fractures with a large width and high longitudinal extension, especially in karst caves, which results in a low pressure-bearing capacity for the plugging layer. Obviously, the type, geometry and mechanical properties of the bridging lost circulation material play a vital role in the bearing capacity of the plugging layer [18].

Drilling fluid loss easily occurs in the drilling process of deep and ultra-deep fractured formations. The fracture plugging layer formed by the bridge lost circulation material is unstable and damaged in a complex environment, such as a high-temperature, high-pressure and high-in-situ-stress environment, leading to the failure of lost circulation control [11]. Kang et al. established an evaluation method and index system for the high-temperature aging performance of bridging lost circulation materials in deep and ultra-deep wells by analyzing the morphology, particle size distribution and mechanical properties of bridging lost circulation materials such as walnut shell and calcium carbonate [19]. The hermite interpolation method can ensure that the function value and the derivative value of the interpolated function at the constructed interpolation polynomial node are equal, and the piecewise low-order Hermite interpolation method can avoid the runge phenomenon caused by the increase in interpolation nodes, and meet the requirements of numerical solution accuracy for general engineering problems. Based on the measured particle size distribution data for single bridging lost circulation material, Zhu et al. proposed a new method to predict the particle size distribution of bridging lost circulation material and formula using the piecewise cubic Hermite interpolation method [20]. To solve the problems of poor retention capacity and the low plugging success rate of conventional bridging lost circulation materials, Li et al. determined the particle size range and volume ratio of different bridging materials, and formed a high-temperature and high-strength cross-linking plugging formula [21].

2.2. High-Water-Loss Lost Circulation Materials and Properties

High-water-loss lost circulation material refers to the lost circulation material that forms a dense plugging layer through solid-phase water loss and by filling in the loss channel [11]. High-water-loss lost circulation materials are generally composed of polymer, diatomite, cement, sepiolite, attapulgite, asbestos powder, stone ridge, filtration materials and inert materials in a certain proportion [22][23]. This kind of lost circulation material will rapidly lose water under the difference between the formation pressure and the drilling fluid column pressure, and the solid phase components will coagulate and thicken to quickly form a film or filter cake to seal the loss channel of the fractures. High-water-loss lost circulation materials are easy to use, and have a quick effect and high success rate in high-permeability strata [24]. However, the high-water-loss lost circulation material is similar to the bridge lost circulation material, which has poor adaptability to the loss channel and is easily washed away in larger fractures or caves [5]. Therefore, high-water-loss lost circulation material is can solve the vertical and horizontal loss zone and the formation of small loss.

Common high-water-loss lost circulation materials are Chevron’s Diaseal M lost circulation material, China’s DSL plugging agent and Z-DTR plugging agent [1]. The lost circulation material with high water loss, high pressure and high acid solubility, mainly composed of fine fiber and granular components, can quickly accumulate lost circulation material and block the loss channel. In the process of waiting plugging, the lost circulation material produces a cross-linking chemical reaction, and finally forms the plugging wall with high-pressure capacity [25]. By optimizing the plugging process and using high-water-loss lost circulation material, the successful one-time lost circulation control with multiple loss points in the same open hole was realized in the Jianmen 1 well, and the plugging effect was obvious.

2.3. Curable Lost Circulation Materials and Properties

Curable lost circulation material refers to lost circulation material with strong thixotropic and curing properties, which can be quickly cured and blocked in the loss layer [1]. Curable lost circulation materials are generally composed of a curing agent, suspension stabilizer and retarder and other materials. Curable lost circulation materials can effectively reside in the lost formation after entrance. Due to its strong thixotropic performance and flow resistance in the loss layer, curable lost circulation material can quickly solidify and coagulate to form a solidified body with high strength, as well as reducing mud and drilling fluid loss [26]. Curable lost circulation material has wide sources, low cost, high strength, a simple preparation process and a high cementation strength after curing. However, its construction safety risk is high, and its resistance to high-salinity formations and water pollution are poor, which can easily lead to problems such as stuck drilling or its being diluted and washed away in fractures or karst caves [27].

Sentinel CemTM cement, developed by the Halliburton company, the MAGNE-SET type curable lost circulation material developed by Baker Hughes Company, HDL-4, and chemical consolidation and cross-linking film composite lost circulation material are common existing curable lost circulation materials [1]. However, in general, curable lost circulation materials have a higher bearing capacity and better curing performance than conventional bridging lost circulation materials. In the process of circulating drilling, the plugging layer will not be destroyed by the pressure of a drilling fluid column, which can greatly reduce the number of plugging operations. When the curable lost circulation material is used with an inert material, the lost circulation control success rate can be effectively improved. Inert materials can bridge and fill the lost layer to achieve the effect of “sealing the door”, while curable lost circulation materials can effectively stay in the lost layer after entering the lost layer to inhibit the loss of drilling fluid [28]. In addition, the curing agent can quickly solidify and condense to form a high-strength plugging layer and improve the lost circulation control effect. When curable lost circulation material is used with a cross-linked polymer, it can form a more stable three-dimensional network structure and achieve the best lost circulation control effect.

2.4. Liquid Absorption Expansion Lost Circulation Materials and Properties

Most of the liquid absorption expansion lost circulation materials are composed of water absorption and oil absorption resin materials, either alone or combined with other lost circulation materials [29]. Its molecular structure contains hydrophilic or lipophilic groups. It swells in water or oil, but does not dissolve. Absorbent expansion polymer lost circulation materials can be generally divided into anionic, cationic, non-ionic and composite ionic. The swelling polymer lost circulation material has the advantages of expansion and deformation and is not affected by the shape and size of the loss channel. It can solve the adaptive plugging problem that the bridge and high-water loss lost circulation material cannot solve [2]. Liquid absorption expansion lost circulation materials, using intermolecular van der Waals force and osmotic pressure difference for the fracture, can absorb water (oil) volume expansion, and form a good elastic filling layer. They are suitable for porous and fractured formations. However, their suction delay effect and temperature-resistance performance are poor, and their plugging applicability is poor in formations with large fractures or karst caves.

Common liquid absorption expansion lost circulation materials are acrylamide–acrylonitrile copolymer, acrylic acid–acrylic acid sodium copolymer polymer swelling resin and its mixture, and other lost circulation materials. In view of the poor stability and low strength of water absorption resin, Wang et al. prepared a water absorption resin type plugging agent PQ with acrylic acid and acrylamide as experimental raw materials [30]. Water absorption rate increased more than 150 times, with good stability. At present, it has problems of poor environmental protection, low strength and high cost. Huang et al. developed a new type of water absorption expansion plugging agent by free radical polymerization using acrylic acid, acrylamide, bentonite, inert materials and initiator as raw materials, which can greatly reduce the cost [31]. Liu et al. developed a micron-sized deformable globular gel, supplemented with optimized flak-like and fibrous lost circulation materials, and synthesized a globular gel compound plugging agent with oil absorption and expansion. Micro-holes and micro-fractures can be blocked while drilling to prevent or reduce oil-based drilling fluid loss.

2.5. Flexible Gel Lost Circulation Materials and Properties

Drilling in the process of formation environment becomes more demanding and the frequency of lost circulation is sharply increased with the gradual exploration and development of oil and gas under deep, ultra-deep, unconventional and other complex conditions [1]. Gel lost circulation materials mainly use chemical crosslinking reactions or interactions between molecules to form a high-strength gel with a three-dimensional network structure to plug the drilling fluid loss channels in complex formations [32][33]. Flexible gel is a kind of lost circulation material, which is suitable for different loss channels, mainly divided into crosslinking gel type and non-crosslinking gel type. Compared with other types of lost circulation materials, flexible polymer gel lost circulation materials can adapt to different scales of loss channels without being limited by their morphology because of their good deformability under compression, and easy to form high strength plugging in the loss channels [33].

Crosslinking gel refers to the injection of a polymer (or monomer), crosslinking agent and initiator into the downhole loss channel in the form of an aqueous solution [34]. The crosslinking reaction generates viscoelastic gel in the formation environment, and then blocks the loss channel [35]. Common cross-linked gels include cross-linked polymer gel, polyacrylamide cross-linked gel, composite nanoscale organic/inorganic gel, underground cross-linked polymer gel, etc. [36]. Non-crosslinked gels are mainly formed by an entanglement or association between polymer chains with special functional groups. In order to solve the problem of drilling fluid loss in geological drilling, Jia et al. prepared an environmentally friendly and strength-enhanced nano-silica composite gel for the temporary plugging of high-temperature reservoirs [37]. The gel had good mechanical and elastic properties. The addition of nano-silica made the three-dimensional network structure of the gel closer, which was conducive to enhancing the lost circulation control effect. Flexible gel lost circulation materials generally have poor high-temperature resistance and long-term stability under high-temperature conditions, resulting in ineffective fracture plugging or a high risk of re-leakage after plugging.

3. Evaluation Method of Drilling Fluid Loss and Lost Circulation Control

Evaluation method of drilling fluid lost circulation control is the key to preventing the loss of drilling fluid and an important basis for the choice of plugging measure. It helps to clarify the characteristics and distribution law of the loss of drilling fluid and establish the dynamic model of the loss of drilling fluid.

3.1. Evaluation Method of Drilling Fluid Loss in Fractured Formation

The determination of the lost zone is the key to successful lost circulation control during drilling. The accurate determination of lost circulation location within a short time can effectively improve the success rate of lost circulation control. There are many kinds of classification methods for drilling fluid loss in fractured formation. The classification of drilling fluid loss in fractured formation can reflect the mechanism of drilling fluid loss from different sides. Among them, the most commonly used method of drilling fluid loss classification is based on the characteristics of drilling fluid loss rate and drilling fluid loss channel in fractured formation [38]. The classification method based on loss rate can reflect the severity of drilling fluid loss as a whole. The classification method based on the characteristics of loss channels reflects the basic form of loss space in fractured strata to a certain extent. At present, foreign countries mainly use well-temperature testers, acoustic testers, eddy current testers, radioactive tracers and other instrument testing methods to determine the location of lost circulation points [8][15]. Domestic experts and scholars have also carried out some active and effective methods to find the lost circulation, such as well-temperature logging, fuzzy identification of the loss zone before the drilling risk prediction method, the comprehensive analysis method, etc. [39][40]. To solve the problem of drilling fluid loss in fractured formation, Zhang et al. divided drilling fluid loss in fractured formation into fracturing loss, expansion loss and differential pressure loss [41]. In order to clearly understand the loss behavior of drilling fluid in rough fractures and fracture networks, experts and scholars at home and abroad established one-dimensional linear, two-dimensional plane fracture and three-dimensional fracture network loss dynamics models based on fractal and Monte Carlo theories, and systematically analyzed the loss law for drilling fluid in fractured formations [42][43]. To understand lost circulation and optimize lost circulation control technology, Xu et al. conducted a study on the diagnosis of drilling fluid loss, established a two-dimensional plane fracture H-B flow model, and revealed the dynamic behavior of drilling fluid loss and its influencing factors [44].

To truly reflect the stress state of fractured formation and the law of fluid loss and flow, Sui et al. invented an experimental device and evaluation method to simulate the dynamic loss and plugging of drilling fluid [45]. This can simulate the positive and negative circulation dynamic loss process of drilling fluid on different core faces under original in situ stress conditions. To accurately grasp the loss situation, and adopt a reasonable and effective lost circulation control method to reduce the loss of drilling fluid, Bai et al. invented a method for predicting drilling fluid loss in fractured formations [46]. The loss of drilling fluid in fractured formations could be accurately predicted by calculating the fracture width, measuring the viscosity coefficient, flow characteristic index and yield stress of drilling fluids. To accurately measure and monitor the status of drilling fluid loss points in fractured formations and evaluate the loss strength of drilling fluid loss points, Jiang et al. invented a drilling fluid loss monitoring system and monitoring method based on the distributed optical fiber sensor [47]. This method could be used to design a lost circulation control technology scheme and conducts measurements according to the loss strength to protect drilling holes and drilling rigs.

3.2. Evaluation Method of Pressure-Bearing Capacity in Fractured Formation

The pressure-bearing capacity of fractured formations is an important index to measure the loss control effect of drilling fluid. It is of great significance for the efficient development of oil and gas resources in fractured formations to effectively improve the formations' pressure-bearing capacity, establish the pressure-plugging prediction model of fractured formations and form the pressure-bearing-capacity strengthening method. At present, the performance of gel lost circulation materials is mainly evaluated by devices and methods such as high-temperature and high-pressure water loss meters, artificial core-simulation crack loss plugging, nano-composite organic/inorganic gel plugging agent devices, and high-temperature and high-pressure water loss meter sand bed evaluation experiments [48][49]. To solve the problem of lost control when drilling fluids in deep fractured formations, Xu et al. constructed an instability model for the plugging layer in fractured formation based on particle mechanics [50]. Based on the strength model of the fracture plugging layer, the instability mechanism of the fracture plugging layer was revealed. In addition, considering the stratum's high-temperature, high-pressure and high-stress conditions, a new type of lost circulation material was selected to establish a quantitative scoring model for lost circulation materials in fractured formations, and a quantitative scoring optimization method was created for lost circulation materials in fractured formations.

An artificial fracture is used to simulate the loss formation channel in the commonly used lost circulation control evaluation devices. Zhu et al. provided a kind of fracture lost circulation control instrument, which could solve the problem with the existing lost circulation control evaluation device, which finds it difficult to simulate the formation loss channel [20]. Experts and scholars at home and abroad generally use the American Petroleum Institute (API, The United States) lost circulation control evaluation experimental device to evaluate and study the plugging ability of lost circulation materials. However, American Petroleum Institute (API, The United States) cannot simulate the re-opening loss of fractures caused by fracture closures under pressure. Therefore, She et al. invented a drilling-fluid pressure plugging fracturing test device [6]. This method can simulate the formation process of real fractures under the action of drilling fluid and the pressure plugging process of lost materials, which provides a new testing method for the research and evaluation of pressure plugging of drilling fluid under the condition of easy to lose formations. The innovation and breakthrough of the basic research on efficient lost circulation control materials and their action mechanisms are key to improving the success rate of lost circulation control in fractured formations.

The following technical challenges occur in the study of lost circulation control evaluation methods and theories in fractured formations: (1) The loss and plugging mechanisms of drilling fluid in fractured formations are not clear; therefore, scientific predictions of the actual properties of lost circulation formation (location of lost circulation, width of fracture and lost circulation pressure) cannot be supported, and technological research, as well as the development of lost circulation control materials, cannot be scientifically guided. (2) The existing bridge plugging materials poorly match the characteristics and types of lost circulation and lack a quantitative evaluation and lack optimization methods of bridge plugging materials for fractured formation. Additionally, the formation and pressure evolution mechanisms of the bridge plugging layer are unclear, and there is no scientific basis for bridge plugging formula design, resulting in a low success rate.

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