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RESEARCH PAPER

Research status and development directions of intelligent drilling fluid technologies

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Abstract: By reviewing the current status of drilling fluid technologies with primary intelligence features at home and abroad, the development background and intelligent response mechanisms of drilling fluid technologies such as variable density, salt response, reversible emulsification, constant rheology, shape memory loss prevention and plugging, intelligent reservoir protection and in-situ rheology control are elaborated, current issues and future challenges are analyzed, and it is pointed out that intelligent material science, nanoscience and artificial intelligence theory are important methods for future research of intelligent drilling fluid technology of horizontal wells with more advanced intelligent features of "self-identification, self-tuning and self-adaptation". Based on the aforementioned outline and integrated with the demands from the drilling fluid technology and intelligent drilling fluid theory, three development suggestions are put forward: (1) research and develop intelligent drilling fluids responding to variable formation pressure, variable formation lithology and fluid, variable reservoir characteristics, high temperature formation and complex ground environmental protection needs; (2) establish an expert system for intelligent drilling fluid design and management; and (3) establish a real-time intelligent check and maintenance processing network.

Key words: intelligent drilling fluid; intelligent additive; intelligent material; nanomaterials; artificial intelligence; expert system

Introduction

Over the past few years, high-efficiency drilling fluid technologies have been developed worldwide, represented by high-temperature and high-density oil-based, soil-free oil-based, high-performance water-based, bionic high-efficiency water-based, and amphiphobic high-efficiency water-based drilling fluids [1–3]. However, as drilling targets change from shallow to deep/extra-deep layers, from conventional to unconventional resources (e.g., shale oil and gas, tight oil and gas, coalbed methane, oil shale and natural gas hydrate), as well as from traditional fossil energy to new energy resources (e.g., hot dry rock), the surface and underground conditions faced by drilling projects are becoming increasingly complex, and it is difficult or even unlikely to accurately predict the formation temperature and pressure system, formation rock composition and structure, formation fluid properties and distribution, the potential damage factors and critical points of the reservoir, the technical difficulties and complexity that may be encountered in drilling, etc. The above limitations have brought great blindness to the selection of drilling fluid types and treatment agents, drilling fluid formulations and performance design, frequently causing several problems (e.g., wall instability, sticking, unclean wellbore, lost circulation, reservoir damage, and environmental pollution). Moreover, the existing drilling fluid theories and technologies have become somewhat inadequate for such problems. According to the statistics of China National Petroleum Corporation (CNPC) in 2017, the complicated drilling fluid situation or accidents in the blocks affiliated to CNPC caused a total of 4122.52 d of time loss, and the economic loss was also highly serious. Under the objective fact that the formation uncertainty is difficult to accurately predict, the key to solving the above drilling fluid technical problems is to enable the drilling fluid to automatically identify the complex downhole environment, adjust the performance

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of the drilling fluid automatically and automatically mitigate or even avoid the occurrence of complex downhole situations or accidents, rather than relying too much on the accurate prediction of downhole complex situations or accidents in advance to design drilling fluids that can avoid or mitigate the above complex situations or accidents. In other words, designing and adopting drilling fluid technology with intelligent features (e.g., "self-identification, self-tuning and self-adaptation") will be conducive to fundamentally solving the technical problems of drilling fluid. This type of intelligent drilling fluid is the future research and development direction and pertains to a higher-grade and more promising drilling fluid type. As revealed by the existing research, drilling fluids with the above intelligent response characteristics have appeared. Nevertheless, the existing research worldwide on intelligent drilling fluids is only at the initial stage of understanding and infancy, the relevant research remains shallow, and the intelligent response mechanism should be further clarified, belonging to the primary stage of intelligent drilling fluid technology. At present, construction methods of the intelligent drilling fluid system and response theory relating to the intelligent treatment agent should be urgently studied in depth to facilitate the development of intelligent drilling fluid theory and technologies.

In this paper, the drilling fluid technologies worldwide with primary intelligent characteristics and their intelligent response mechanism are first classified and summarized, and the current problems and future challenges of primary intelligent drilling fluid technologies are analyzed in depth. Subsequently, the future development direction of intelligent drilling fluid is highlighted to lay a basis for scholars to develop more intelligent drilling fluid materials and systems and to propose perfect intelligent drilling fluid theories and technologies.

1. Technology status of primary intelligent drilling fluids

In 2016, Iranian scholar Ghojogh [4] first proposed that a novel generation of "intelligent drilling fluid" can be prepared by introducing intelligent materials/fluids to drilling. Intelligetnt drilling fluids are conducive to achieving successful drilling in difficult drilling areas with incompetent conventional drilling fluids, minimizing the cost of treatment agents, and facilitating the sustainable use of drilling fluids. A drilling fluid consisting of one or more intelligent drilling fluid additives that can autonomously identify changes in the downhole environment and adapt itself to the downhole environment by adjusting its physical or chemical properties is termed “intelligent drilling fluid”. In the following, several primary intelligent drilling fluid technologies worldwide with certain intelligent characteristics are presented, and their development background and intelligent response mechanism are primarily analyzed.

1.1. Variable density drilling fluid based on pressure sensitive materials

During drilling, the drilling fluid should balance the formation pressure. In the current drilling design, the reasonable drilling fluid density and the corresponding wellbore structure are mainly designed in accordance with the three pressure profiles. The comprehensive well construction cost is generally high. Variable density drilling fluid refers to a drilling fluid whose density can automatically change with the depth of the well, mainly including basic fluid and intelligent variable density additives [5]. The state of this intelligent variable density additive can vary with downhole pressure (Fig. 1), with the largest volume-to-weight ratio when the additive is in a fully expanded state at low pressure and the smallest volume-to-weight ratio when it is fully contracted at high pressure, so the system density can increase with the increase of downhole pressure. Compared with the traditional drilling fluid technology, the variable density drilling fluid can be pre-designed to adjust the amplitude and direction of the density change of the system, so the system can automatically adjust the density under the downhole pressure, which can effectively reduce the casing layer, extend the depth of the wellbore, and increase the depth of the wellbore, significantly reducing the cost of well construction [6–9]. Spiecker et al. [10] also developed a drilling system that was applied in conjunction with the variable density drilling fluid technology. This drilling system is capable of monitoring the wear of the intelligent variable density additive particles during the use cycle to effectively control the content of intelligent variable density additive in the system and obtain a suitable downhole additive density distribution, which shows promising applications.

1.2. Saturated salt-water drilling fluid based on salt-responsive polymers

The occurrence of “polyelectrolyte effect” [11] during

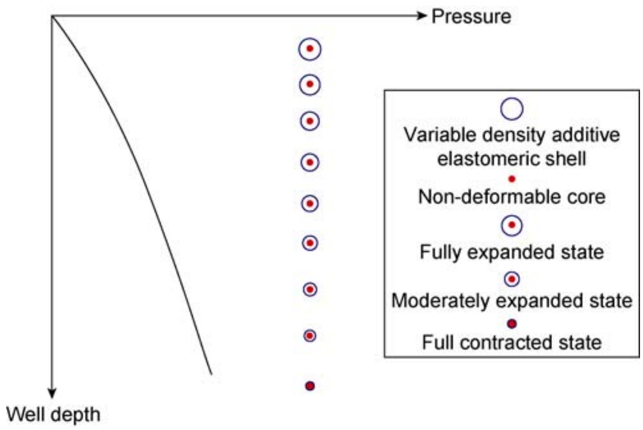

Fig. 1. Change of state of intelligent variable density additive with downhole pressure.

drilling in high-salt environment (e.g., salt-gypsum layer) can easily result in the failure of conventional polymer treatment agents and trigger the instability of the drilling fluid system, and the introduction of strong hydrophilic groups (e.g., sulfonic acid groups) [12] can enhance the hydration ability of salt-resistant polymers to a certain extent. However, if the time is too long, the anti-salt and high-temperature resistance effects of the system remain poor. A special zwitterionic polymer with equal anionic and cationic charges refers to a salt-responsive smart polymer, exhibiting a special "anti-polyelectrolyte effect" in high-salt solutions [13], i.e., when it is stimulated by salt ions, the conformation of the polymer molecular chain will vary from curling to stretching, and the higher the salt content, the more conducive it will be to exerting its anti-salt effect.

Given the above findings, Jiang et al. [14] prepared two salt-responsive zwitterionic smart polymers with high molecular weight and low ionicity (HvL) and low molecular weight and high ionicity (LvH) by inverse emulsion polymerization, respectively. The viscosities of HvL and LvH solutions with a mass fraction of 2% increased with the increase of salt content (mass fraction of 0.5%, 5.0%, 15.0% and complete saturation). Moreover, with HvL and LvH as the core additives, a salt-responsive saturated salt-water drilling fluid was prepared. The system has good viscosity stability before and after hot rolling at 150 °C, high ratio of yield point to plastic viscosity and low filtration loss. It is capable of resisting the pollution of bentonite with a mass fraction of 30% and $CaCl_2$ pollution with a mass fraction of 0.75%. The system exerts a good application effect in CNPC Western Drilling Engineering Co., Ltd. It addresses the problem that conventional polymer drilling fluids are difficult to resist salt at high temperatures and under high densities, and realizes the change of passive salt resistance to active salt resistance of the drilling fluid.

1.3. Reversible emulsification drilling fluid based on pH-responsive materials

Reversible emulsification drilling fluid (oil-based or synthetic-based drilling fluid) has the advantages of thin filter cake, low friction, good wellbore stability and good effect of protecting reservoir. However, there are technical problems such as difficulty in removing well wall filter cake, low cementing strength of the second interface and difficult disposal of oily drill cuttings and waste slurry. In 1998, Patel initially developed a reversible emulsification drilling fluid containing acid-based surfactants [15–16]. This drilling fluid can easily and reversibly convert between water-in-oil emulsions and oil-in-water emulsions when stimulated by acid and alkali. The stable conversion mechanism between emulsions is illustrated in Fig. 2. This technology has been successfully applied in areas such as Central Graben in the North Sea.

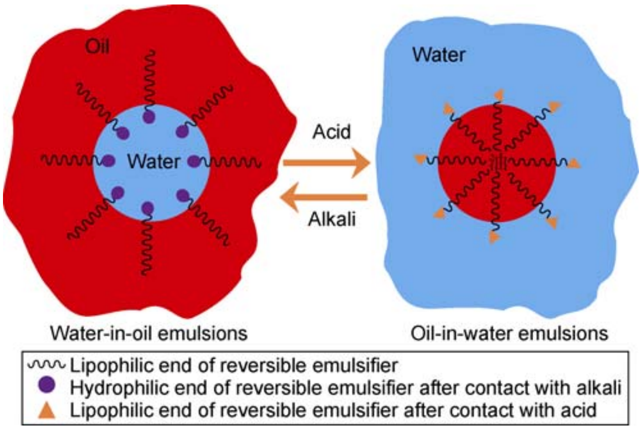

Fig. 2. Interconversion between the water-in-oil emulsions and oil-in-water emulsions.

Organic amines (e.g., amidoamine) [17–20] have been commonly used as reversible emulsifiers, and the nitrogen atoms in the hydrophilic polar groups are correspondingly protonated ($R—NH^{3+}$) or deprotonated ($R—NH^2$) with the change of acidity and alkalinity, thus changing the HLB value (hydrophilic-lipophilic balance value) of the surfactant and realizing the transformation of the emulsion type [21]. Over the past few years, the reversible Pickering emulsion has developed rapidly. The emulsion is mainly composed of colloidal-sized solid particles adsorbed on the oil-water interface to form a monolayer/multilayer film to achieve stability. By adjusting the pH value of the water phase or the electrolyte concentration, the affinity of the solid particles can be adjusted, so as to achieve the phase inversion of the emulsion. This method shows the advantages of low cost, environmental friendliness and good stability. There are many types of solid particles used for reversible Pickering emulsions, such as Fe_3O_4 nanoparticles covered with oleic acid, polystyrene latex particles, etc. [22–23]. Scholars worldwide have also developed different stimuli-responsive reversible emulsions based on temperature, salinity and light control [24–26], further broadening the response range of reversible emulsions. Ren et al. [27] prepared a reversible emulsification drilling fluid by using organic amine surfactants. As revealed by the evaluation result, the system exhibited high performance before and after phase inversion, with a demulsification voltage of 500–900 V and a temperature resistance of 180 °C. With the use of this technology in the process of offshore oil and gas drilling, the drilling cuttings processing procedure can be simplified, the amount of waste discharged to the seabed can be reduced, and the pressure on environmental protection can be more effectively reduced. Thus, this technology shows promising applications [28–30].

1.4. Constant rheology drilling fluid based on thermosensitive polymer

With the development of offshore oil exploration into deep water and ultra-deep water, the technical challenges facing deep water drilling are becoming increasingly severe. In particular, the low-temperature thickening of drilling fluids leads to an increase in the ECD (equivalent circulating density) at the bottom of the well, which can easily lead to downhole complicated situations such as lost circulation. The key to solving this problem is to weaken the sensitivity of drilling fluid viscosity and shear force to temperature, as well as to keep rheological parameters basically constant within a certain temperature range [31–32]. Van Oort et al. [33] developed a synthetic-based drilling fluid system with constant rheological properties for the first time. The low shear rate viscosity, dynamic shear force and gel strength of the system were basically constant in the range of 4.44–65.56 °C, which is highly conducive to the stability of the ECD. The constant rheological properties of drilling fluid can be achieved in two ways. One is to use the weak viscosity-increasing effect of a small amount of organic soil particles at low- temperature and the stretching and viscosity-increasing effect of temperature-sensitive polymer molecular chains at high-temperature to reduce the sensitivity of viscosity and shear stress to temperature of the system [34–35]. The second one using the organic soil with temperature-activated surfactants to form a spatial network structure whose strength changes with temperature, thus reducing the sensitivity of system viscosity to temperature. Both of the above methods will lead to a complementary transition in the rheological properties of the drilling fluid, i.e., when the viscosity reduction of the system at high temperatures cannot be fully compensated by the increased viscosity of the polymer or surfactant, the rheological properties of the system will appear in "U"-shaped curve features [36–38]. The study of Shi et al. [39] further highlighted that the excessive amount of organic soil is not conducive to the constant rheology, and a small amount of high-quality organic soil can prevent the soil from dispersing into colloidal particles in the pure oil phase and increase the viscosity of the continuous phase. The interaction between high-quality organic soil and dispersion liquid provides viscous shear. As a result, when the oil-water ratio is high, the system exhibits low viscous shear and good low-temperature rheology. Young et al. [40] adopted a novel type of emulsifier and amide temperature-sensitive polymer with both emulsifying and surface wetting abilities to overcome the shortcomings of the first-generation synthetic-based drilling fluid system developed by Van Oort et al. The formulation of the second-generation system is simpler, the gel strength is lower, and the temperature resistance can reach 176.7 °C, which has been successfully applied in the Gulf of Mexico and other regions [41].

1.5. Intelligent plugging system based on shape memory material

Loss of circulation usually accounts for 60% of all downhole complications or accidents, and it has been found as the main factor for the increase of non-productive drilling time and well construction costs [42]. To prevent or eliminate lost circulation, a variety of lost circulation materials [43] and lost circulation theories [44–45] have been developed worldwide. However, it is usually very difficult to predict the pore throat size and distribution of the lost formation, and the success rate of plugging cannot be guaranteed. Thus, based on the basic theory of shape memory materials [46], scholars at home and abroad have developed high-efficiency pressure-bearing plugging materials exhibiting intelligent characteristics. The advantages of adjustable response temperature and response time, low density, good mechanical properties, self-adaptation bridging and plugging, etc., show a good application prospect of leakage prevention and plugging. Meng et al. employed the mixture of Portland cement and bentonite as the outer shell, and the mixture of shape memory alloy and chopped cotton fiber wound into a spring filament as the core, successfully prepared a spherical shape memory alloy with a diameter of 4–20 mm as the intelligent plugging materials [47–48]. Shape memory polymers have been extensively applied in petroleum engineering [49], including cement intelligent expansion agent for oil well cementing [50], intelligent expansion proppant and diverting agent for hydraulic fracturing, etc. [51]. It shows promising applications. Mansour et al. [52–53] applied shape memory polymer as an intelligent temperature-sensitive expansion plugging agent for the first time to plug fractured formations. By increasing the circumferential stress of the wellbore, the wellbore was strengthened, and the wedge-shaped fractured plate with a fracture width of 1.00–2.54 mm can be successfully blocked, and the bearing pressure can reach 34 MPa. Wang et al. [54] well prepared temperature-sensitive expandable intelligent plugging agents with different response temperatures (50–100 °C) and expansion ratios (5%–110%) using shape memory epoxy resin composite foam as the matrix. It has a good sealing and pressure-bearing effect on both the large-porosity sand disc and the sand bed. Sun et al. [55] proposed the concept and mechanism of various novel intelligent plugging materials (e.g., second-order curing shape memory intelligent plugging materials, intelligent self-healing gel plugging materials, strong cementation intelligent membrane materials and intelligent bionic plugging materials), which have effectively facilitated the development of intelligent plugging technology.

1.6. Drilling fluid for protecting reservoir based on intelligent temporary plugging

The damage of oil and gas layers will have a significant effect on the effective discovery of oil and gas reservoirs and the initial production of oil and gas wells. Shielding temporary plugging [56–57], fine temporary plugging [58–60] and physical and chemical film temporary plugging [61–63] have been established, as well as other reservoir protection technologies, so the protection effect of oil and gas layers is progressively enhanced. The shielding temporary plugging and the fine temporary plugging technologies are effective under the premise of accurately knowing the pore throat size and distribution of oil and gas layers in advance, while this premise is difficult to achieve in practice. The physical and chemical membrane temporary plugging technology weakens the size matching to a certain extent, whereas it is difficult to avoid the damage arising from high instantaneous filtration loss. The firm strength is always lower than that of shielding ring, and it is difficult to form in medium-high permeability strata. Thus, Jiang et al. applied the principle of bionics into the field of oil and gas reservoir protection and developed three bionic drilling fluid technologies for temporary plugging and protection of oil and gas reservoirs with different permeability, i.e. synergistic synergy type, biofilm type, as well as super-amphiphobic type [64–68]. It is only necessary to know the reservoir permeability grade without an accurate prediction of the pore-throat size, and the reservoir can be self-adaptively plugged temporarily, thus showing the characteristic of certain primary intelligence.

For low-permeability and ultra-low-permeability oil and gas layers, Jiang et al. developed a super-amphiphobic agent based on the super-amphiphobicity of the surface in the mouth area of Nepenthes [64–66], which can form micro-nano papillary structures on the rock surface of oil and gas layers and effectively reducing the surface tension of the rock. Under 3% aqueous solution, the core surface tension can decrease to 0.80 mN/m, the core surface is hydrophobic and oleophobic, and the water and oil contact angles increase from 2° and 1° to 152° and 165°, respectively. Subsequently, the capillary force of the reservoir reverses to the resistance, which prevents the liquid phase from entering the reservoir and causing damage. For medium permeability oil and gas layers, a film-coated amphiphilic polymer super-hydrophobic agent showing rigid and flexible structures was developed based on the hydrophobic and self-cleaning properties of the lotus leaf surface [67]. Its micro- and nano-scale rigid structure can block oil and gas layer pore throat. The flexible structure is capable of forming films with pore throat, enhancing the strength of plugging film and changing the wettability of rock surface. After the core surface was treated with super-hydrophobic agent, a layer of micro-nano papillary structure was formed, the surface tension was reduced from 62 mN/m to 17 mN/m, the water contact angle increased from 18.11° to 165.00°, and the borehole wall was cleaned. For high-permeability and ultra-high-permeability oil and gas layers, a biomimetic high-strength and super-tough layered composite material was developed based on the alternating multi-layer composite structure of shell “brick-mud” [68]. The assembly structure method of multi-scale and multi-grade “brick-mud” is capable of forming a solid and dense shielding temporary blocking zone, while achieving the "ultra-low" damage target of high-permeability oil and gas layers.

1.7. In-situ rheological control of drilling fluid based on magnetically responsive particles

Rheological in-situ control of drilling fluid refers to a drilling fluid technology based on intelligent fluids. With the addition of intelligent magnetic Fe_3O_4 nano-additives into drilling fluids, intelligent in-situ rheological controllable drilling fluids with "timely and controllable" rheological properties can be developed under an external magnetic field. Vryzas et al. [69] employed ferrous salts, iron salts and sodium hydroxide to prepare smart magnetic Fe_3O_4 additives using the precipitation method. They produced customized magnetic Fe_3O_4 nanoparticle bentonite suspensions with two mass fractions (including 0.5% and 1%, with the mass fraction of bentonite of 7%) and investigated the in-situ rheological controllability of the suspensions under the action of ambient temperature and certain strength of external magnetic field. As revealed by the results of the magnetorheological measurements, the yield stress of the in-situ rheological controllable drilling fluid increased by over 75% under a magnetic field of 0.1 T. After a 0.7 T magnetic field was applied, the maximum variation of yield stress of a 1% in-situ rheological controllable drilling fluid was 609%, and the viscosity of the in-situ rheological controllable drilling fluid increased monotonically with the magnetic field strength at different shear rates. After the applied magnetic field was removed, the average deviation of the rheological curve before the application was nearly 20%, thus suggesting the potential of using magnetic nanoparticles to prepare intelligent drilling fluids exhibiting reversible rheological properties.

2. Problems and challenges of intelligent drilling fluid technology

The existing intelligent drilling fluid technology is only in its infancy and still faces numerous problems and challenges. Under the prediction of the safe density window of the drilling fluid, the variable density drilling fluid technology can be used to moderately change the density of the drilling fluid by adjusting the volume to mass ratio of the intelligent variable density additive, so the density of the drilling fluid can be always within the safe drilling fluid density window. However, there have been significant errors in the prediction of the three types of downhole formation pressures. Moreover, when the formation pressure changes significantly, the variable density drilling fluid technology cannot achieve complete self-adaptation, i.e., the degree of self-adaptation or intelligence to the formation pressure is low. As a result, the intelligent adaptability of the variable density drilling fluid technology should be further improved.

The intelligent anti-salt additive based on salt-responsive zwitterionic polymer is capable of recognizing the change of the salt content of the drilling fluid and leading to the positive and moderate changes of the viscosity and shear force of the system by adjusting the conformation of its own molecular chain. On that basis, the intelligent anti-salt additive can adapt to the high-salt environment in the well. However, this technology lacks the ability to respond to high-valent cations (e.g., calcium ions).

The reversible emulsification drilling fluid technology integrates the advantages of oil-based drilling fluid and water-based drilling fluid. In addition, it can be easily converted into oil-in-water drilling fluid during well completion and subsequent stages, improve the quality and efficiency of filter cake and cuttings cleaning, and enhance cement bonding strength, etc. Besides, this technology is conducive to simplifying marine waste treatment procedures and reducing environmental protection pressure. However, the response rate of reversible emulsification drilling fluid to pH changes is relatively slow, and the rheology and fluid loss stability of the system before and after the emulsion type change remain poor.

The constant rheology drilling fluid technology enables the drilling fluid to identify the downhole temperature environment automatically, and it can achieve the constant viscosity and shear force of the system under the compensation effect of polymer molecular chains and organic soils under temperature stimulation, so as to adapt to the high- and low-temperature circulation environment in the well. However, there has not been any unified theoretical explanation for the realization mechanism of the constant rheology of the current constant rheology drilling fluid technology, and in-depth research should be conducted to reduce the difficulty in achieving the constant rheological characteristics. Moreover, the lower temperature limit of most drilling fluid constant rheological studies is nearly 4 °C, and it is unlikely or difficult to achieve constant rheological properties at ultra-low temperatures. The surface temperature can reach −40 °C or even lower in Xinjiang and Northeast China or South Pole, and the temperature of the drilling fluid circulating out of the wellhead will immediately decline to approximately −10 °C. Accordingly, the constant rheology drilling fluid technology adapting to lower temperatures should be further developed to satisfy the drilling requirements of the extremely cold region.

The intelligent plugging system based on shape memory material enables the plugging fluid to identify the temperature of the leakage layer and leads to the shape change of the plugging fluid through the shape recovery of the intelligent shape memory additive, which can enhance the plugging ability of the plugging fluid to the loss channel. However, the existing intelligent plugging system has poor ability to identify and adapt to the shape of the lost channel, and it can only deform based on the established shape recovery method. Research should be conducted on the plugging fluid to automatically identify the shape of the lost channel and realize intelligent plugging, and further increase a plug "Bionic temporary plugging" protection of oil and gas reservoir drilling fluid technology has weakened the dependence on the pore throat size of oil and gas reservoir. This "weak" dependence can be realized in design and construction, which makes the protection of oil and gas reservoir have the characteristics of primary intelligence, but the degree of intelligence needs to be further improved. In the future, it is necessary to develop intelligent oil and gas protection technology that does not need to consider the permeability level (low, medium, and high) of oil and gas reservoir.

The rheological in-situ regulation of drilling fluid technology enables the drilling fluid to identify changes in magnetic field strength, and to achieve rheological regulation by adjusting the connection between magnetic particles. Further exploration is needed to obtain an in-situ regulation of intelligent drilling fluid system formulations with comprehensive and excellent properties (e.g., fluid loss, inhibition, lubricity). Moreover, the technology of rheological in-situ control of drilling fluid requires the application of a magnetic field at a specific location downhole. Thus, a special downhole tool that can apply a magnetic field to the fluid should be developed to verify and improve the field application effect of this intelligent drilling fluid system.

3. Future development directions and approaches of intelligent drilling fluid technology

The future-oriented intelligent drilling fluid technology should introduce the frontier theories and technologies of material science (e.g., intelligent materials science, nanoscience, and bionic materials science) into the research and development of the existing drilling fluid intelligent additives and the establishment of the optimal system, while developing a series of intelligent drilling fluid additives with higher intelligence features and developing the intelligent drilling fluid technology based on the technical requirements of drilling fluids. Moreover, intelligent data transmission, processing and application technologies should be developed. And the artificial intelligence, big data, cloud computing, internet of things and other computer or communication frontier scientific theories and technologies should be introduced into drilling fluid data management and analysis and processing. Multi-disciplinary and integrated research is conducted to create an original, more mature and more intelligent "intelligent drilling fluid theory and technology", and facilitate the intelligent revolution of drilling fluid technology.

3.1. Variable density intelligent drilling fluid in response to variable formation pressure

Impacted by the inevitable errors in formation pressure prediction, formation pressure is very difficult to balance, especially when drilling into abnormal pressure system wells (e.g., high and low pressure in the same layer or coexistence of multiple pressure layers). Accordingly, it is also necessary to develop variable density drilling fluids that respond to variable formation pressures, so the intelligent variable density additive has the ability to identify the actual formation pressure downhole and adjust the structure accordingly. As a result, the drilling fluid density can adapt to the actual downhole safe density window in real time, reduce the risk of wellbore instability and lost circulation caused by prediction errors, and improve drilling safety.

3.2. Intelligent drilling fluid responding to variable formation lithology and variable formation fluid properties

During the drilling process, minerals from the formation rock or formation fluid enter the drilling fluid system, which will trigger the imbalance of the original chemical stability of the drilling fluid and result in a significant deterioration of key properties (e.g., rheology, filtration and lubrication of the drilling fluid). In general, the sources of formation pollution to drilling fluids consist of swellable clay minerals, gypsum, formation fluids (e.g., brine), H_2S, etc. It is necessary to further develop intelligent response additives and intelligent drilling fluids that adapt to the above pollution factors. In addition to improving the responsiveness of salt-responsive polymers to high-valent cations (such as calcium ions), the addition of intelligent polymers with selective adsorption capacity for expansive clay minerals and chemical materials that can react with H_2S to automatically maintain the alkalinity of drilling fluid are also needed. The drilling fluid can automatically identify pollution sources from formation rocks and fluids, and adjust its performance to adapt to the changing environment of downhole formation lithology and formation fluids.

3.3. Intelligent drilling fluid responding to environmental protection needs of high-temperature formation and complex ground

The high temperature at the bottom of the hole poses a serious challenge to the temperature resistance of the drilling fluid. Sulfonating the drilling fluid polymer treatment agent or using oil-based drilling fluid can significantly improve the temperature resistance of the drilling fluid. However, the above drilling fluids will bring serious pollution to the environment, and the post-processing is difficult and costly. The reversible emulsification drilling fluid technology is more friendly to the surface environment in terms of reducing the amount of oily drilling cuttings, and can further develop high temperature resistant reversible emulsifiers suitable for high temperature and high density drilling fluid systems. For constant rheological drilling fluid technology, in addition to the need to further develop low-temperature flow regulators that meet the needs of extremely cold regions, in order to meet the needs of onshore deep well drilling, it is also necessary to consider the development of high-temperature resistant intelligent additives based on temperature-sensitive polymer materials. A novel type of intelligent anti-high-temperature tackifier or flow pattern modifier can be developed using temperature-sensitive monomers with high-temperature thermal tackifying effect (e.g., N-isopropylacrylamide (NIPAM), N-vinyl caprolactam (NVCL)). The high-temperature and environment-friendly intelligent drilling fluid system can be formed. On the one hand, it improves the stability of the viscosity and shear force of the drilling fluid in the high-temperature environment at the bottom of the well, and on the other hand, it reduces the environmental pollution caused by additives, and truly realizes the unity of high-temperature resistance and environmental protection.

3.4. Drilling fluid for intelligent protection of oil and gas reservoirs in response to changing reservoir characteristics

Temporary plugging type intelligent drilling fluid technology for oil and gas layer protection should know the pore throat size distribution or permeability level of oil and gas layers in advance. However, impacted by the heterogeneity and complexity of the reservoir, the reservoir characteristics of different layers in the same well interval may vary significantly. It is necessary to develop drilling fluid technology for intelligent protection of oil and gas layers in response to changing reservoir characteristics, so the drilling fluid can identify reservoirs and meet the protection requirements of different types of reservoirs without relying on predicted reservoir characteristics, and the plugging layers can be degraded, which takes on a great significance for timely discovery of oil and gas resources and avoidance of oil and gas reservoir damage. Shape memory degradable polymers (e.g., degradable polylactic acid bases) exhibit shape memory and degradable properties, and can be employed to design smart temporary plugging materials for protection of oil and gas reservoirs. After the plugging materials enter the loss layer, the shape recovery is achieved under the excitation of formation temperature, so as to realize the plugging of loss layers of different sizes. Subsequently, the plug removal can be achieved by thermal degradation or enzymatic degradation, thus contributing to subsequent oil and gas production.

3.5. Expert system for intelligent drilling fluid design and management based on big data, cloud computing and artificial intelligence technology

At present, a unified expert management and decision-making system has been developed, which can integrate information (e.g., selection of drilling fluid types, formulation design, performance optimization, introduction and use of treatment agents, key maintenance measures and downhole complex conditions). Effective processing and mining of structured and unstructured historical data (e.g., application well basic information, drilling fluid formulation and performance, drilling parameters, and downhole complex conditions) can't be achieved. Knowledge mining can be conducted through machine learning, artificial intelligence and other methods to provide basis and decision-making reference for drilling fluid design and optimization, and on-site accident prevention and treatment. Based on big data and cloud computing technology, a drilling fluid management database is built to analyze the massive history data of drilling fluids. The hidden, potential, regular and valuable information in the database is employed for knowledge mining. Artificial neural networks, support vector machines and other machine learning methods are adopted to analyze the existing data through algorithms, and the correlation model of performance of drilling fluid, drilling parameters (e.g., rate of penetration, friction torque, drilling cycle) and downhole complex conditions (e.g., well collapse and stuck pipe) is established through training. Thus the expert decisions for drilling fluid design, drilling plan, accident prevention and treatment are provided. The intelligent drilling fluid design and management expert system is capable of implementing digital management of drilling fluid, which takes on a critical significance to the digitalization and information construction of oil and gas enterprises.

3.6. Intelligent detection and maintenance processing technology of drilling fluid performance based on real-time monitoring and transmission of 4G/5G network

The continuous reduction of computer hardware costs, the maturing of software technology, and the development of 4G/5G network communication technology have created unprecedented sufficient conditions for oil and gas companies to facilitate digitalization and informatization construction. With the development of "drilling data", the collection, analysis and application of first-hand data in the construction process provide valuable reference and guidance for the design and actual drilling of subsequent construction wells, and are of great significance for improving drilling speed, preventing and reducing complexities and accidents and reducing drilling costs. The current intelligent monitoring technology of drilling fluid performance mainly realizes real-time monitoring or prediction of key performance parameters of drilling fluid (e.g., density, rheology, fluid loss), but automatic monitoring technology for other performance parameters of drilling fluid (e.g., pH value, conductivity, lubrication coefficient, sand content) need to be developed to obtain the comprehensive performance of the drilling fluid. Moreover, the remote monitoring technology of drilling fluid performance should be further developed, and the 4G/5G communication network should be adopted to timely transmit the drilling fluid data and drilling data (e.g., text, images, videos) collected on the spot to the database in real time for real-time sorting and analysis. In addition, to develop a mobile application (e.g., Android or iOS) of the drilling fluid expert intelligent system, if you have a mobile phone or tablet, a strong team will be organized, ranging from drilling fluid calculation tools to accident recording and handling. All can be integrated into a small mobile terminal, thus increasing the work efficiency of technicians and saving costs.

4. Conclusions

Intelligent drilling fluid technology is considered an effective means of avoiding blindness in drilling fluid design, reducing downhole complex situations or accidents, achieving safe and efficient drilling, and reducing costs and increasing efficiency. It is the need to realize the construction of intelligent oilfield and the inevitable trend of future development of drilling fluid technology.

At present, several primary intelligent drilling fluid technologies have been developed worldwide. The drilling fluid can initially identify changes in the external environment of the fluid (e.g., downhole pressure, temperature and magnetic field) and changes in the internal environment of the fluid (e.g., pH value and salinity), and adjust its physical and chemical properties (e.g., density, rheology, and emulsification type) through intelligent additives. So as to preliminarily solve the technical problems that the drilling fluid in the oil field is susceptible to formation fluid contamination, loss and reservoir damage, thus showing the characteristics of primary intelligence. The degree of intelligence is significantly low, and it is basically in its infancy. Besides, intelligent drilling fluid technology should be further developed with more advanced intelligence.

Aiming at the international scientific and technological frontier and the development trend of the international petroleum industry, the further development of intelligent drilling fluid technology requires the use of intelligent materials, nanoscience, bionics and other theories to develop novel intelligent drilling fluid additives and intelligent drilling fluid systems, so the drilling fluid can achieve the partial or comprehensive response of the downhole environment (e.g., variable pressure and temperature, variable formation lithology and fluid properties, and variable reservoir characteristics). Besides, artificial intelligence, big data, cloud computing, 4G/5G communication, etc. that have emerged over the past few years should be also used. With the technological development of drilling fluid intelligent monitoring technology and more advanced expert systems, more mature and "intelligent drilling fluid theories and technologies" with higher intelligence can be formed, and the drilling fluid technology can be promoted to truly enter the era of intelligence.

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