ISSN 2712-8008
Volume / Том 21 №3 2021
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

WELL DRILLING AND COMPLETION TECHNOLOGIES

UDC 622.276:622.24.063-047.37
Article / Статья

Research of Bare-Free Drilling Fluids

Ekaterina L. Leusheva, Nazim T. Alikhanov

Saint Petersburg Mining University (2 21st Line, Vasilyevsky island, Saint Petersburg, 199106, Russian Federation)

Исследование безбаритных буровых растворов

Е.Л. Леушева, Н.Т. Алиханов

Санкт-Петербургский горный университет (Россия, 119106, г. Санкт-Петербург, Васильевский остров, 21-я линия, 2)

Received / Получена: 01.02.2021. Accepted / Принята: 30.04.2021. Published / Опубликована: 01.07.2021

Keywords:
abnormally high pressure, weighting additives, inorganic salts, environmentally friendly drilling fluids, drilling in difficult conditions, thermal stability, rheological parameters, formation inhibition, prevention of salt formation dissolution, prevention of sticking, complications during drilling, treatment of bottomhole formation zone, preservation of reservoir properties.

Mining and geological conditions for the development of new fields are becoming more difficult every year. Accordingly, the requirements for ensuring the environmental and technological safety of the drilling process are becoming more and more important. To ensure such a process, it is necessary to use correctly selected drilling fluids with proper characteristics: rheological parameters sufficient for effective cleaning of the well bottom, density sufficient to create back pressure, fluid loss to ensure a high-quality filter cake. Modern environmental requirements dictate the abandonment of hydrocarbon-based solutions. But when using water-based solutions, there are no suitable solutions, especially with their high density, since the use of barite can lead to a decrease in reservoir productivity. In this regard, the analysis of the problem and the search for options for creating water-based drilling fluids, weighted without the addition of barite, having the properties of maintaining the stability of the wellbore, ensuring safe drilling and opening productive formations without damaging the reservoir characteristics, was carried out.
Such a solution was found in changing the base of the drilling fluid - highly mineralized fluids or solutions based on saturated brines. Brines must be created on the basis of inorganic salts that have good solubility, for example, chlorides, bromides. Due to the content of salts, the fluids have an inhibitory effect, and depending on the volume of dissolution, the density of the drilling fluids can be controlled.
The scientific works of foreign and domestic scientists analyzed in the article have been published over the past five years, which indicates the relevance of this development. The selected compositions are presented and theoretically investigated, which were also tested in the field conditions.

Ключевые слова:
аномально высокое давление, утяжеляющие добавки, неорганические соли, экологически безопасные буровые растворы, бурение скважин в осложненных условиях, термостабильность, реологические параметры, ингибирование пластов, предотвращение растворения соляных пластов, предупреждение прихватов, осложнения во время бурения, обработка призабойной зоны пласта, сохранение коллекторских свойств.

Горно-геологические условия разработки новых месторождений с каждым годом становятся сложнее. Соответственно все более важными становятся требования по обеспечению экологической и технологической безопасности процесса бурения. Для обеспечения такого процесса необходимо использовать правильно подобранные буровые растворы с надлежащими характеристиками: реологические параметры, достаточные для эффективной очистки забоя скважины, плотность, достаточную для создания противодавления, водоотдачу для обеспечения качественной фильтрационной корки. Современные экологические требования предписывают отказ от растворов на углеводородной основе. Но при использовании растворов на водной основе нет подходящих решений, особенно при их высокой плотности, так как применение барита может привести к снижению продуктивности пластов. В связи с этим осуществлен анализ проблемы и поиск вариантов для создания буровых растворов на водной основе, утяжеленных без добавления барита, обладающих свойствами сохранять стабильность ствола скважины, обеспечивать безопасное бурение и вскрывать продуктивные пласты без нанесения ущерба коллекторским характеристикам.
Такое решение было найдено в изменении базы бурового раствора – высокоминерализованные растворы или растворы на основе насыщенных рассолов. Рассолы необходимо создавать на основе неорганических солей, которые обладают хорошей растворимостью, например хлориды, бромиды. Благодаря содержанию солей растворы обладают ингибирующей способностью, а в зависимости от объема растворения можно управлять плотностью буровых растворов.
Научные работы иностранных и отечественных ученых, проанализированные в статье, опубликованы в течение последних пяти лет, что говорит об актуальности данной разработки. Представлены и теоретически исследованы избранные составы, которые также были опробованы в промысловых условиях.

Ekaterina L. Leusheva (Author ID in Scopus: 56609312400) – PhD in Engineering, Associate Professor at the Well Drilling Department (tel.: +007 911 709 71 47, e-mail: Leusheva_EL@pers.spmi.ru). The contact person for correspondance.
Nazim T. Alikhanov – Master's student (tel.: +007 950 228 05 76, e-mail: n.alikhanov@gmail.com).

Леушева Екатерина Леонидовна – кандидат технических наук, доцент кафедры бурения (тел.: +007 9117097147, e-mail: Leusheva_EL@pers.spmi.ru). Контактное лицо для переписки.
Алиханов Назим Теймурович – магистр (тел.: +007 9502280576, e-mail: n.alikhanov@gmail.com).

Please cite this article in English as:
Leusheva E.L., Alikhanov N.T. Research of Bare-Free Drilling Fluids. *Perm Journal of Petroleum and Mining Engineering*, 2021, vol.21, no.3, pp.123-130. DOI: 10.15593/2712-8008/2021.3.4

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Леушева Е.Л., Алиханов Н.Т. Исследование безбаритных буровых растворов // Недропользование. – 2021. – Т.21, №3. – С.123–130. DOI: 10.15593/2712-8008/2021.3.4

Introduction

Creating a drilling fluid for pay drilling or working on an existing well requires a deep understanding of the reservoir specifics. Damage mechanisms during pay drilling include fine solids flow, clay swelling, drill-in fluid (DIF) incompatibility with the formation fluid, and the use of formation damaging reagents that can reduce the average formation permeability, resulting in lower production rates [1].

A suitable drilling fluid must not chemically react with the rock and formation fluid being drilled and must be non-invasive to maintain the original rock condition. To create such a solution, it is necessary to correctly select the type of cake-forming particles, particle size distribution and concentration, based on the reservoir rock morphology [2]. When properly selected, a dense, thin filter cake is quickly formed, preventing the penetration of filtrate and small drilling particles into the formation, minimizing the formation damage and the possibility of differential pipe sticking [3].

Onset of the development of deposits in abnormal geological conditions was a matter of time. However, there were no suitable drilling fluids in the industry. The use of barite as the main weighting agent in drilling fluids has led to a lack of alternatives in the market. These two factors have caused a number of emergencies and complications at opening the deep-lying oil and gas reservoirs [4].

The current situation formed the goal of this work - to study the compositions of weighted barite-free drilling fluids.

Justification of the Need to Study and Use Weighted Barite-Free Drilling Fluids

Drilling fluids are required to drill oil and gas wells. Such drilling fluids perform a number of tasks: they are pumped through drill pipes so that the fluids come out, lifting all the cuttings; in case of stopping drilling, the fluids keep the cuttings in suspension, lubricate and cool the bit, protect oil and gas formations from clogging, but one of their most important roles is the replacement of cuttings to prevent the fluid intrusion and wellbore integrity damage [3, 5]. At first, ordinary water could act as a drilling fluid, such fluids were later called self-mixing. However, the easily recoverable oil fund has depleted, and for the extraction of hydrocarbons it is necessary to develop deposits that lie much deeper. Such deposits are mainly composed of low-rate and low-permeability reservoirs in abnormal operating conditions. Since the entire drilling process is characterized by high pressure, temperature, salinity [6], the modern oil extraction projects cannot do without the use of new technologies - both at drilling and developing an oil and gas reservoir [7].

Overpressure prediction is very important for well planning and safe drilling [8, 9]. However, accurate and reliable prediction requires an understanding of such overpressure origin and distribution.

Overpressure (abnormally high formation pressure) poses a serious geological hazard and a drilling issue. The petrophysical properties of sediments are influenced by various mechanisms generating the abnormally high pressure. There are two different mechanisms for generating overpressure, specifically: rock compaction and fluid expansion, each of which has different petrophysical features and, therefore, different forecasting techniques [6, 10, 11].

Improved knowledge of the overpressure mechanisms and pore pressure distribution in the formation provides the critical support information for the hydrocarbon exploration and production team. This information not only has a direct impact on the drilling cost and safety, but also provides insight into the key data for producing the drilling fluid [12].

When selecting and producing a drilling fluid composition for drilling in abnormally high formation pressure (AHFP) areas, it is necessary to take into account a number of factors to prevent gas-water-oil shows (GOWSs) and maintain rheological characteristics at high temperatures [13]. Currently, a technology gap has emerged, presenting a challenge for the development of high-density water-based drilling fluid systems for high pressure and high temperature (HPHT) wells. The gap arose is caused by impossibility to generate a suitable rheology due to the deposition of weighting agents, changes in performance due to temperature rise down the wellbore, high concentration of solids to produce weighted drilling fluids, decreased polymer efficiency due to lack of free water, poor filter cake quality, leading to sticking and deterioration of reservoir properties [3, 14, 15]. Working in a narrow window between pore pressure and fracture initiation pressure adds complexity to drilling fluids maintenance, where a small change in bottomhole pressure can lead to a significant increase in non-productive time (NPT) due to the time spent on resolving possible losses and fluid manifestations [16, 17].

As a result of understanding the mechanism of wellbore destruction in clayey areas, the practice of using fluids spiked with salts, which began to call inhibitory, has appeared [18, 19]. However, even calcium, sodium, and potassium cations entering the shales from the fluid have a different effect due to the different diameters of hydrated ions [20–22].

Clay is not the only cause of wellbore wall instability, but salt deposits also create difficulties. Practice has shown that the solution is the same approach as used with clay - it is necessary to saturate the fluid with salt. But this only works in the case of low seams, because at thicknesses of more than a kilometer, heterogeneity can often be recorded when aggressive formations, providing the wellbore instability, are found due to their tendency to flow under pressure. In this case, a system with the addition of three salts at once, for example, sodium, potassium and magnesium chlorides, is used. It is necessary to add protective reagents: carboxymethyl cellulose (CMC), starch - to monitor water loss, structural and mechanical properties of the fluid, because when drilling deep formations, weighted fluids should be used, and kinesthetic stability is significant for them [3, 15, 23].

In addition to wellbore instability, the use of a water-based fluid when drilling in productive zones leads to clogging. It may happen due to several reasons [15]. Firstly, this is a water-loss, water penetration adversely affects the reservoir permeability, because when water is mixed with formation fluids, an emulsion preventing the further flow of fluids is formed. Secondly, the fluid particles can penetrate and clog the pores, and the size of these particles is an important factor in determining the penetration depth. To prevent clogging, a high-quality filter cake, which would restrain the penetration of liquid and solid phases into the formation, is required. However, it is especially difficult to create such a cake when using weighted drilling fluids.

Hydrocarbon-based fluids are widely used since they have clear advantages over water-based drilling fluids. Advantages include stability in water-sensitive formations where a water-based fluid (WBF) would result in a narrowing of the wellbore. Wellbore stability is achieved with oil-based fluids by limiting the natural tendency of clays to absorb water from water-based drilling fluids [24]. When using oil-based drilling fluids, water emulsified in the oil phase can be used with increased salinity, thereby decreasing the flowing water from the formation due to osmotic forces. This additionally stabilizes and strengthens the well [25, 26].

Oil-based drilling fluid (OBF) compared to WBF has other advantages, in particular, it provides better lubrication, and it has also been established that the use of oil-based drilling fluids can lead to a significant increase in drilling rate. Such advantages are important, especially in deep-seated deposits, requiring large investments. All this dictates the need to drill as many wells as possible from one point, which implies large horizontal deviations of wells using directional drilling methods in order to exploit difficult-to-reach hydrocarbon deposits or find suitable places for water injection. This fluid has long been the main fluid for opening and drilling productive formations, due to the above properties and a hydrocarbon base that does not conflict with formation fluids [24, 25, 27].

However, the use of this fluid has some drawbacks. The very first drawback is their high cost. Second, they include the toxicity of some aromatic compounds, chemical reagents and the diesel base itself [2, 28, 29].

OBF also differs from the water-based fluids in its compressibility, which leads to a strong dependence of the fluid density on temperature and pressure [30]. As a result, depending on the content of solid and liquid phases, the OBF density can change at drilling, and if this is not taken into account, the consequences can be catastrophic [17, 31].

In the industry, for a long time, the solution was to use oil-based drilling fluids, and barite was used as a weighted agent, which, to ensure high hydrostatic pressures, was set to the required density [18].

The main advantage of barite is the density that can be created by adding it to the fluid. Due to the lack of analogues, it is used, despite all the shortcomings, and they can cause serious problems. To begin with, it should be noted that this fluid is insoluble in water, as a result of which maintaining the barite particles in suspension is a difficult task. The more the fluid is in a static state, the more barite is deposited, and if the drill stem is down the hole, the deposited barite will certainly cause sticking. If an extra-weighted drilling fluid is required, more barite should be added to it, which increases the solid phase load. In such cases the cake may be thick and loose, which can lead to the drill stem sticking. When drilling horizontal well sections, all sludge will accumulate on this cake, and a plug will form, which will take time to eliminate. If there was no sticking, then the accumulation of barite and sludge down the hole will become a problem for the start of circulation, it will be necessary to set a high pressure, which the pump and the formation may not withstand, and this is in its turn will lead to an accident and stop drilling or a complication that requires elimination [32]. To solve the problem, it is necessary to create such a rheology, which usually leads to a high equivalent circulation density (ECD), the addition of a large amount of expensive stabilizers, structure-forming agents [33, 34]. If the formation fluids penetrate into the solution, a rapid deterioration of its structural and mechanical properties will occur, which will again lead to the solid phase precipitation [16].

Barite is insoluble not only in water, but also in acids, such as: perchloric, formic, citric and acetic. It is known that the filter cake must be formed at drilling, but after that it must be cleaned in order to restore the reservoir permeability. In the case of using barite, the cake will necessarily contain its particles, and part of it will penetrate into the pores, and it will be impossible to remove it using acid treatment. Thus, even before the production onset, the reservoir properties will become worse, and it will be necessary to intensify the flow or artificially form the new pores. All that negatively affects the final oil recovery and the economic feasibility of this project development. Barite also reduces the benefits of projects due to its high price [28, 35, 36].

Study of Barite-Free Drilling Fluid Compositions and Properties

The current situation with difficult drilling conditions, when a high density of drilling fluid is required, and barite is an unprofitable option, led to the search and study of new weighting agents. Hematite, manganese tetroxide were used as an alternative to barite, but they also created a high solid phase load in the fluid, without imparting the density that barite could achieve. Therefore, the studies have been continued, and another way to eliminate barite or at least reduce its content in the fluid, specifically, to produce a drilling fluid based on saturated brine, was found [56]. Chinese institutions and companies, e.g., one of the largest global companies SaudiAramco, and such service companies as Halliburton, BakerHuges, Schlumberge, pay great attention to this study.

Special attention should be paid to works in which new compositions of such fluids and their use in practice are provided. One of these works is a study [28] focused on drilling and development of an ultra-deep reservoir under the Tian Mountain in China. At the deposit, 70 wells were successfully drilled using OBFs, since the use of WBFs was impossible due to long non-working hours as a result of accidents. However, the problem was the adverse environmental impact due to exposure to toxic sludge and chemicals contained in the drilling fluid [28]. Since, when using WBF, one of the sources of problems was the salt and gypsum formations, which contaminated the fluid, that, in turn, led to a change in rheology and brine development, so it was decided to replace the water base with zinc bromide saturated brine. This salt is freely soluble in water, but it was chosen due to its density of 4.219 g/cm^3, which allows setting the fluid density to 2.3 g/cm^3 without a weighting agent.

A number of experiments have been performed, and their results presented. The first is the ageing test. For this, the fluid was exposed to a temperature of 160 °C for 16 h. The results showed that the composition has a good rheology under high pressure and temperature conditions (High temperature high pressure - HTHP). At 25 °C, the fluid density is 2.34 g/cm^3, plastic viscosity - 92 mPa•s, and yield point (YP) - 17 Pa. After 16 hours processing at 160 °C, density increased by 0.2 units, which indicates the complete dissolution of fluid salt, plastic viscosity increased

Table 1

Rheological characteristics of the fluid after experiment

	Conditions	ρ, g/cm^3	μ, mPa·s	PV, mPa•s	YP, in Pa	GEL, Pa/Pa	pH	HTHP, mL/mm
Fluid	25°C	2.34	109	92	17	5/5	–	–
	160 °C · 16 h	2.36	126.5	104	22.5	5/6.5	8	7/2

Table 2

Rheological characteristics of the fluid after ageing

Parameter	Fresh mud	Fluid as rolled	Fluid at Day 3
600 v/w	83	90	107
300 v/w	51	56	67
200 v/w	38	42	51
100 v/w	23	25	33
6 v/w	3	4	6
3 v/w	2	3	5
10 s	2	2	4
10 mins	2	2	4
PV	32	34	40
YP	19	22	27
HP/HT Filtration Test at 350 F, ceramic disc (10 micron)			
Instant filtering	–	–	0
Water loss	–	–	2.2
Filter cake thickness	–	–	1.5875

Fig. 1. Sludge when passing through:
a – gypsum rock (6,675 m); *b* – salt formation (7,600 m)

up to 104 mPa•s, and YP increased up to 22.5 Pa, which is a good result [28]. For clarity, we present the results for a fluid of the following composition: saturated brine + 1 % K_2CO_3 + 0.5 % ND-259 + 1.4 % ND-288 + 1 % ND-253 + 0.2 % NaOH + 1 % ND-258 + 1.5 % HM. Thickener: ND-259. Water-loss control: ND-258. Lubricant: ND-253. Inhibitor: HM. Weighting agent: ND-288.

This drilling fluid composition was successfully applied in the KS 8-5 well. In practice, the inhibition of salt formations by fluid was assessed (Table 1).

From the photographs of sludge (Fig. 1) taken by an engineer on the drill stem, it can be seen that the sludge have a normal shape, and the traces of bit cutters are preserved on it. In addition to that, the average increase in the diameter of salt formation wellbore is 4.24 %, and in formations above the salt is almost 1 %. All this confirms that the fluid is able to inhibit salt rock at high temperature, pressure and salinity [28]. As a result, the following conclusions about the developed fluid were made:

- high pressure salt formations are drilled smoothly to maintain the wellbore stability, as well as the correct wellbore diameter;
- the drilling fluid effectively solved the problem of pipe sticking in salt formations and wellbore instability, while avoiding the pipe sticking or other incidents caused by drilling fluid, which leads to safe drilling operations;
- when using a water-based fluid, the drilling team encountered the pipe sticking on six wells and 4 times with GOWSs. When using OBF, only one sticking and 3 times with GOWSs were recorded. The brine-based fluid solved the problem of non-production time and increased the ROP, thus increasing the drilling efficiency;
- the fluid can be recovered and reused in other wells, thereby reducing the cost of drilling. This fluid composition has brought potential technical and economic benefits to the drilling industry by providing strong technical support for the efficient development of ultra-deep oil deposits in western China.

The next work of interest is the study of brines of two salts: $CaBr_2$ and $CaCl_2$ [2]. The choice of calcium salts is justified by the fact that, for example, sodium salts, chlorides, bromides cannot provide a density higher than 1.2 g/cm^3, a fluid of potassium formate does not exceed a density of 1.3 to 1.4 g/cm^3, For this reason they add cesium formate, which is very expensive and not economically suitable.

Structure-forming agents and water-loss control agents can be considered the two most important components in drilling fluids. As a rule, these are polysaccharides and their derivatives, soluble in water [37].

Chemicals to develop the fluid structure, such as xanthan gum, scleroglucan and diutan, can thicken a variety of monovalent and divalent brines. Such fluids exhibit excellent thixotropic properties, which is directly related to the suspension properties of drilling fluids. This is very beneficial because it helps the fluids to perform one of the main tasks - to carry solids and drill sludge more efficiently to the surface; and when drilling is stopped, it prevents solids and sludge against depositing on the well bottom [38]. In order to minimize fluid loss at drilling, other biopolymers, such as starch, are also often added to provide fluid filtration control. However, due to the chemical nature of these biopolymers, they are not suitable for temperatures above 300 ˚F. Several synthetic polymers were designed for high temperature water-based drilling fluids HP/HT [2].

The choice of polymers was guided by several conditions. First of all, polymers should be able to thicken the brine and impart thixotropic properties to it for effective bottom-hole cleaning and sludge removal [39, 40]. Second condition is a decrease in water loss to preserve the reservoir properties. Third, polymers must be thermally stable and maintain rheological characteristics for at least three days [38, 41].

Before experiment, $CaBr_2$ brine was treated with a small amount of lime and filtered, and $CaCl_2$ brine was only filtered before use. The freshly prepared fluid sample was autoclaved at 150 ˚F for 16 hours and then aged at an elevated temperature. Depending on the ageing conditions, the drilling fluid sample was statically held at 450 ˚F for 16 hours or at 400 ˚F for three days [2, 38].

Fann 35 and 77 were used to measure viscosity under different conditions. Maximum values: temperature – 400 ˚F, pressure - 10,000 psi [2]. Filtration tests were performed at 350 ˚F and 500 psi for 30 minutes, and the results were multiplied by 2 to determine the total water loss of the mud. Reservoir impacts were measured using a Chandler Model 6100 on sandstone.

The samples were hot rolled at 150 ˚F for 16 hours prior to viscosity measurements. Synthetic polymer-based drilling fluid has rheological properties, which are very similar to those of biopolymer fluid. Both fluid samples exhibit excellent thixotropic properties at a low-shear-rate (0.17 s^{-1}) viscosity ranged 3.000 to 5.000 avg and a high-shear-rate (1.021 s^{-1}) viscosity of about 45 avg [2]. High viscosity at low shear rate is a direct indication that sludge and other solids will be efficiently carried to the surface, preventing solids against settling when drilling stops Low viscosity at high shear rate is desirable to reduce pump pressure and minimize the possibility of rock burst [38]. After measuring the viscosity, the samples underwent the reheat test. They were held at 300 ˚F (biopolymer sample) and 450 ˚F (synthetic polymer sample) for 16 hours. Before static ageing, both fluid samples are white and homogeneous. After ageing, biopolymer sample turned dark brown with significant sediment. In the second sample, only a slight discoloration was observed [42]. Moreover, the sample still looked homogeneous with no obvious separation or sedimentation. The viscosity of synthetic polymer drilling fluid was re-measured and a slight increase compared to the pre-ageing sample was found [2]. Then, the aged sample underwent the filtration test on a 10 μm disc at 350 ˚F with a pressure drop of 500 psi. Fluid loss at HT/HP was only 5.4 mL after 30 minutes.

The above results demonstrate the exceptional thermal stability of HT polymer compared to standard biopolymers. A drilling fluid prepared from HT polymer is stable at 450 ˚F for at least 16 hours, which increases the temperature limit for drilling fluids by at least 150 ˚F. Moreover, HT polymer provides excellent fluid filtration control even after exposure to extremely high temperatures [2, 38].

To assess the thermal stability of synthetic polymer fluid over a long period of time, another drilling fluid sample was prepared. After hot rolling at 150 ˚F for 16 hours, the sample was kept at 400 ˚F for three days (Fig. 2, 3). No solid phase separation or sedimentation was observed after static ageing. As with the sample held at 450 ˚F for 16 hours, the sample viscosity increased slightly after ageing, indicating excellent thermal stability. The rheology remained stable, which indicates the preservation of thixotropic properties of the fluid. The sample also maintained good water loss, just 2.2 mL after 30 minutes. The results are shown in Table 2 [2].

Since the drilling fluid particulates are soluble in acid and can be removed by acidizing, the potential formation damage by the polymer becomes significant. It has been shown that branched polymers generally provide less

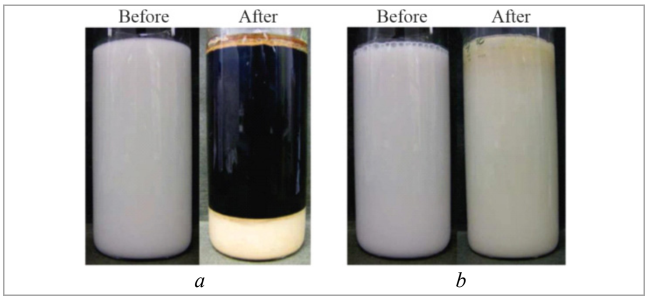

Fig. 2. Post-ageing fluids: *a* – biopolymer at 300 °F, 16 hours; *b* – HT-polymer at 450 °F, 16 hours

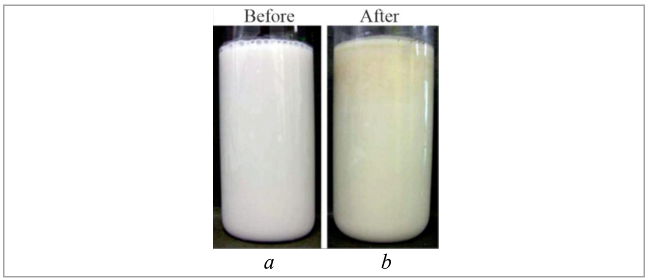

Fig. 3. Fluid: *a* – initial; *b* – after three days of ageing

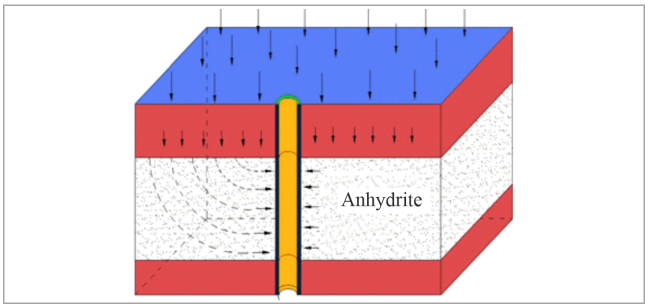

Fig. 4. Reasons for stability violation in the bore hole walls

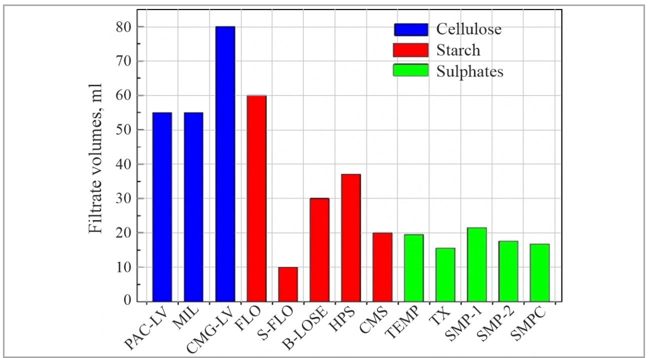

Fig. 5. Filtrate volumes

formation damage than linear polymers. It is expected that polymer particles will accumulate on the formation surface instead of invading the pores. In this case, the polymer particles after acidizing can be easily lifted from the surface, and the damage will be minimal [2].

According to the all above, the researchers managed to develop a high density drilling fluid composition with excellent rheological characteristics and thermal stability, as well as absolute reservoir safety.

Potential formation damage is one of the most important criteria when choosing a drilling fluid and is largely associated with the penetration of particulates or polymers [4, 15].

The "Study and development of a new brine-based drilling fluid for drilling salt and anhydrite formations" research was presented in 2019 at the International Conference on oil and gas engineering and is dedicated to the issue of formation development in the Missan deposit located under the salt and anhydrite formations of high thickness. An anhydrite layer with a thickness of 800 m is a trap in the deposit. However, due to that, there is a threat of reservoir instability associated with the salt ability to flow under conditions of overlying pressure and due to horizontal stress, as well as its dissolution with WBF, which will inevitably lead to a number of accidents at drilling (Fig. 4) [21].

Drilling experience at Missan Oilfield shows that salt an anhydrite formations dissolve easily, which promotes plastic flow and recrystallization of salts, leading to sticking of the drill stem, casing damage and drilling fluid deterioration [21]. Soft mudstone often loses its support due to possible dissolution and formation collapse. Therefore, it is a significant threat to drilling. This is why the decision was made to develop a new brine-based drilling fluid ensuring the safe and cost-effective drilling.

The researchers have identified the following criteria for a new drilling fluid system [21, 43]:

– firstly, its components must effectively restrain the dissolution of salt rock for the sake of wellbore stability;

– secondly, polymers must be salt-resistant to effectively preserve the drilling fluid properties;

– thirdly, a high density of the drilling fluid should be provided to balance the creep of the salt-anhydrite formations in order to avoid drilling accidents such as wellbore collapse, inflow of formation fluids and drill pipe sticking.

Experiments have been developed to investigate the rheology and filtration of brine solutions with various additives before and after the ageing procedure to identify suitable chemicals. The fluid ageing was carried out for 16 h at 100 °C. This ageing is required to determine the drilling fluid stability and adaptability.

A mixture of salts can be used to increase the system properties, such as inhibition, density, saturation. Typically, three monovalent cationic salts are used for fluid preparation: sodium chloride (NaCl), potassium chloride (KCl) and sodium formate (HCOONa), which are cost effective in terms of density adjustment [19, 21]. Formula for a brine-based fluid with a fixed salinity: fresh water + 25wt.% NaCl + 5wt.% KCl + 8wt.% HCOONa, through which a saturated brine can be obtained. In this system, NaCl is used as the base salt of the complex brine system and makes the system in a partially saturated state; KCl is required to increase inhibition against the salt and anhydrite formation; HCOONa may not only increase the density, but also enhance the ability to inhibit the system [43].

Undoubtedly, the created solution with the maximum allowable salinity provides key advantages: on the one hand, the system will have an extremely low solubility in relation to external salts due to the saturated state; on the other hand, the solids concentration required to increase the weight to a high density can be reduced, which will contribute to the stability of the wellbore. Experimental samples were developed with the addition of three common types of stabilizers - polyacrylamides (PHPA, PLH and PLUS), cellulose (PAC and CMC) and biopolymers (VIS, XC, XAN and MC-VIS) - to assess their efficacy in the brine-based fluids in order to select the appropriate stabilizer [22]. Composition of the brine-based drilling fluid: fresh water + 0.6 % viscosifier + (25 % NaCl + 5 % KCl + 8 % HCOONa).

It is clear that biopolymers exhibit better rheology than other types of thickeners collected herein. For polyacrylamide and cellulose types, both apparent viscosity (AV) and plastic viscosity (PV) show a large difference before and after ageing, indicating a poorer rheological stability in a brine-based system. Comparing the rheological characteristics of samples with biopolymers, VIS can be chosen as the main structure-forming component of the developed brine-based drilling system. Moreover, it is environmentally friendly due to its potential for degradation [21, 43].

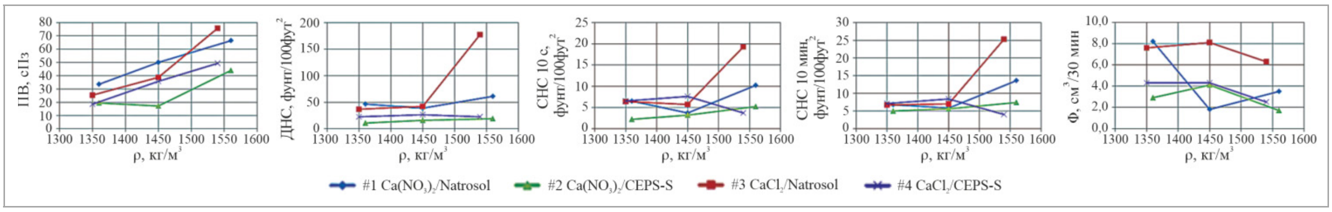

Fig. 6. Influence of fluid density on parameters: PV – plastic viscosity, GEL – static gel strength, F – filtration, YP – yield point

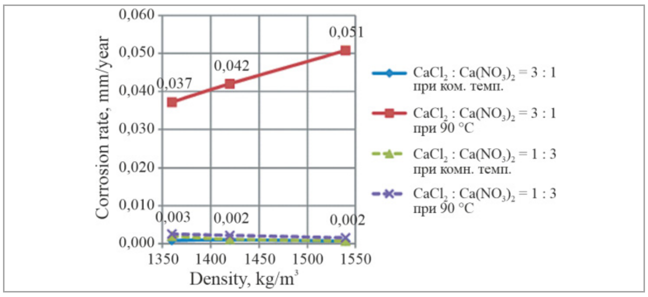

Fig. 7. Corrosion rate at different fluid densities

Next, we'll look at the three main types of water-loss control chemicals: cellulose, starch, and sulfates. Composition of the tested drilling fluid is unchanged. It was decided to add 2 % reagent to reduce filtration.

In contrast to structure-forming agents, all filtration reducing reagents provided the good rheological characteristics. It can be assumed that this was due to the correct choice of polymer for thickening. However, it is wrong to choose such a reagent based on rheology; it is necessary to consider the filtrate volume. The results are shown in Fig. 5 [21].

Cellulose-based reagents produce the largest filtrate volume, which means the worst filtration reduction. In contrast, sulfates show the consistently lower filtrate volumes - less than 20 mL. It should be noted that the potential environmental risk associated with the sulfate treatment of fluids may, to a certain extent, limit their use [21, 44]. With regard to starch reagents, there is a great deal of variability in the values, where S-FLO, the modified starch, better copes with water-loss control, the volume is 10 mL.

To summarize, the basic formula for brine-based drilling fluid is: fresh water 0.6wt. % VIS + 2wt. % S-FLOr + (25wt. % NaCl + 5wt. % KCl + 8wt. % HCOONa). The designed brine-based drilling fluid will not only be resistant to salt contamination, but by its nature will be inactive to salt and anhydrite formations [21].

Experiments in the development of mineralized fluids are also available in domestic practice. At the Volga-Uralsk deposit, the formations are composed of mudstones, which leads to the wellbore wall instability, making it difficult to conduct geophysical works. Well construction can only be completed by re-drilling weighted areas. Finding a solution to the problem is devoted to study by V. Zhivaeva, O. Nozhkina and V. Kapitonov [45]. They identified reasons for the current situation: insufficient density and low inhibiting ability of the fluids used. These problems are inherent in all horizontal wells in the Syngoi and Bazhenov formations of Western Siberia.

When drilling well sections with a zenith angle greater than 60°, there is a non-admission of casing strings due to wellbore narrowing. The main prevention method was to increase the concentration of inhibiting reagents. But that is not a solution, since the total solids content increases. For weighting purposes, the concentration of calcium carbonate is made above 300 kg/m³, which adversely affects the rheological characteristics of the fluid (increased rheology leads to increased hydrodynamic loads on the wellbore walls during circulation, and this contributes to the cavings and fracturing) [45].

For the construction of extended horizontal sections in such conditions, it is necessary to use drilling fluids with a density of 1.4 to 1.5 g/cm³, but creation of such a density with classical weighting agents leads to negative consequences: increased rheology, cake thickness, and impossibility of controlling the fluid properties at low shear rates. The aforementioned cause difficulties during RIH/POOH, high pressure on the pumps when flushing the well, and the occurrence of critical moments of the drill stem rotation [36]. The authors propose a drilling fluid system, the density of which is set by inorganic salts, specifically, calcium chloride and nitrate. Such fluids are not a momentary solution to problems; it is necessary to find the optimal ratio of salt concentrations for a synergistic effect, study the hazard posed by the corrosive activity of divalent metal brines, and select polymers for highly mineralized fluids [45].

Based on previous studies, it was revealed that starch reagents and cellulose ethers are widely used as polymers. These biopolymers have a number of disadvantages, firstly, they can create a high rheology, which is not suitable for the drilling regime used, and secondly, their temperature range imposes limitations on applicability [19, 22, 38].

The authors decided to try a new polymer designed specifically for use in highly mineralized fluids - CEP-S, polyvinyl alcohol derivative with thermal stability up to 100 °C [22]. The task was to develop a drilling fluid composition with minimum rheological and filtration characteristics at the highest possible density. For testing purposes, the fluid samples were prepared on a mixture of calcium chlorides and nitrates with the following densities: 1.35; 1.45; 1.56 g/cm³. These fluids were divided into groups depending on the prevalence of inorganic salt and reagents controlling the water loss: CEP-S and Natrosol (hydroxyl ethyl cellulose) [45].

Analyzing the test result graphs (Fig. 4), it should be noted right away that CEP-S in samples with higher density and concentration provides less liquid phase filtration than fluids using hydroxyl ethyl cellulose (HEC) as a stabilizer [46]. At the same time, HEC-based fluids have high values of plastic viscosity and yield point. Thus, CEP-S stabilized fluids correspond to the optimal values of rheological characteristics, specifically: plastic viscosity does not exceed 35 cP and yield point is less than 26 lb/100 ft². Filtration rate was 4 cm³/30 min, and under high pressure and temperature conditions it did not exceed 8 cm³/30 min. Since the fluid is developed for drilling long horizontal sections, thixotropic properties are very important, and fluids with CEP-S have the best structural and mechanical properties - this is 7/8 lb/100 ft² (10 s/10 min) [45].

For the developed compositions of drilling fluids with various densities, created by changing the ratio of chloride to calcium nitrate concentrations, the studies on their corrosivity were carried out in accordance with GOST. The studies were carried out both under surface and wellbore conditions with heating up to 90 °C. To determine the most suitable salt ratio, the studies were carried out without the addition of corrosion inhibitors. It is commonly known that corrosion depends on the fluid pH. If the environment is acidic, corrosive activity increases. The preferred corrosion value is less than 0.12 mm per year, which can only be achieved at pH 7 to 8.5 [12, 14]. The study results are presented by the authors in the form of a diagram shown in Fig. 7 [45].

According to data in Fig. 7, corrosion rate of fluids with a predominant content of calcium nitrate salts in the mixture does not change during ageing under surface and wellbore conditions, which indicates a low corrosivity of the studied sample. For fluid containing more calcium chloride, the situation is different: at room temperature, the corrosion rate is 0.003 mm per year and does not change with increasing density, but the same fluids at high temperatures take on values that increase significantly. Despite this, even the highest value, 0.051 mm per year, is within acceptable limits. Thus, corrosion rate can be controlled by adjusting the calcium nitrate content as well as by adding a small amount of alkali. The most significant finding is the evidence that there is no significant relationship between corrosion rate and temperature. According to the study result, these fluids have properties suitable for practical use [45].

According to the studies carried out, the authors identified the optimal compositions of drilling fluids that should be tested in practice, and in case of positive data, they can be used in other deposits with similar mining and geological conditions. For the first practical experiments, we may recommend a composition with a predominant content of calcium nitrate and CEPS-S biopolymer, since this fluid has suitable rheological characteristics at optimal pseudoplastic flow [47]. This fluid contains a minimum amount of solid phase, is resistant to the colloidal phase and characterized by minimal filtration, which has a positive effect on the properties of productive formations. In addition to all the advantages, the fluid is reusable and easy to prepare [45].

Conclusions

1. The transition to the development of deposits in abnormal operating conditions entails to use the weighted drilling fluids, where the main weighting agent is barite.

2. Usually, productive formations are opened with hydrocarbon-based fluids, their use in abnormal operating conditions is a less profitable option due to its high cost and environment impact. The use of water-based fluid with barite is an even bigger problem.

3. In the market, there are no technological solutions for safe drilling with weighted barite-free water-based drilling fluid.

4. The issue of barite replacement is relevant all over the world, since its use is technologically impracticable.

5. Currently, there is a large number of studies devoted to the creation of drilling fluids weighted with inorganic and organic salts.

References

1. Mathieu Champeau, Wei Xia, Jackson Phillip, Sui Changping, Zhang Joyce, Okhrimenko Albert. Alternative High Density Brines. *Day 2 Wed, 2019, September 04. D021S009R007*. Aberdeen, UK: SPE, 2019. DOI: https://doi.org/10.2118/195743-MS
2. Zhou Hui, Deville Jay P., Chesnee L. Davis. Novel High Density Brine-Based Drill-In Fluids Significantly Increased Temperature Limit for HP/HT Applications. *D012S020R003*. London, England, UK: SPE, 2015. DOI: https://doi.org/10.2118/173075-MS
3. Fattah K.A., Lashin A. Investigation of Mud Density and Weighting Materials Effect on Drilling Fluid Filter Cake Properties and Formation Damage. *Journal of African Earth Sciences*, 2016, vol. 117, pp. 345-57. DOI: https://doi.org/10.1016/j.jafrearsci.2016.02.003
4. Al-salali Yousef Zaid, Al-Bader Haifa, Vidyasagar D., Manimaran A., Packirisamy S., Al-Ibrahim Abdulla. Paradigm Shift in Reducing Formation Damage: Application of Potassium Formate Water Based Mud in Deep HPHT Exploratory Well. *All Days. SPE-163301-MS*. Kuwait City, Kuwait: SPE, 2012. DOI: https://doi.org/10.2118/163301-MS
5. Sukhoboka O. Drilling Fluid Rheology Under High Pressure High Temperature Conditions and Its Impact on the Rate of Penetration. *Day 1 Wed, April 05. 2017, D011S003R001*. Bergen, Norway: SPE, 2017. DOI: https://doi.org/10.2118/185916-MS
6. Wagle Vikrant, Abdullah S. Al-Yami, Mohammad Aljubran, Hussain Al-Bahrani. High Density Drilling Fluids for Managed Pressure Drilling. *All Days, SPE-192248-MS*. Dammam, Saudi Arabia: SPE, 2018. DOI: https://doi.org/10.2118/192248-MS
7. Davydov A.V., Pogretskii A.V., Smirnov O.A., Lukashov A.V., Pravdukhin A.P., Kurchikov A.R., Borodkin V.N. Chaiandinskoe mestorozhdenie - proekt vnedreniia novykh tekhnologii v Vostochnoi Sibiri [Chayandinskoye field is the project of new technologies implementation in East Siberia]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2017, vol. 16, no. 2. DOI: https://doi.org/10.15593/2224-9923/2017.2.2
8. Moradi S.S.T., Nikolaev N.I., Chudinova I.V. Geomechanical Analysis of Wellbore Stability in High-pressure, High-temperature Formations. *Proceedings of the Eage Conference & Exhibition*, Paris, France, 12-15 June 2017. DOI: 10.3997/2214-4609.201701463
9. Moradi S.S.T., Nikolaev N.I., Chudinova I.V., Martel A.S. Geomechanical study of well stability in high-pressure, high-temperature conditions. *Geomechanics and Engineering*, 2018, vol. 16(3), pp. 331-339. DOI: 10.12989/gae.2018.16.3.331
10. Islamov Azamat, Dmitriy Kolupaev, Ruslan Faskhutdinov, Sergei Vereschagin. On the Mechanisms of the Formation of Zones with Abnormally High Rock Pressure and Methods for Predicting Them in Undeveloped Rock Systems. *Day 2 Tue, 2018, October 16. D023S013R007*. Moscow, Russia: SPE, 2018. DOI: https://doi.org/10.2118/191501-18RPTC-MS
11. Dvoynikov M.V., Kuchin V.N., Mintzaev M.Sh. Development of viscoelastic systems and technologies for isolating water-bearing horizons with abnormal formation pressures during oil and gas wells drilling. *Journal of Mining Institute*, 2021, vol. 247, pp. 1-9. DOI: 10.31897/PMI.2021.1.7
12. Il'in I.A. Model' vnutrisolevykh raponasyshchennykh plastov, oslozhniaiushchikh protsess bureniia skvazhin Astrakhanskogo GKM [Model of the intrasalt brine formations that complicate the well drilling at Astrakhan gas condensate field]. *Gazovaia promyshlennost'*, 2020, iss. 4 (799), available at: https://elibrary.ru/item.asp?id=43812968
13. Ilinova A., Chanysheva A. Algorithm for assessing the prospects of offshore oil and gas projects in the Arctic. *Energy Reports*, 2020, vol. 6, pp. 504-509. DOI:10.1016/j.egyr.2019.11.110
14. Makhamatkhozhaev D.R., Ekubova F.B., Saidov T.S. Bureniia skvazhin v solenosnykh otlozheniiakh AO «Uzburneftegaz» v usloviiakh rapoproiavleniia [Well-drillings in saliferous deposits of JSC "Uzburneftegaz" in the conditions of rapoproyavleniya]. *Bulatovskie chteniia*, 2018, vol. 3, pp. 175-180, available at: https://elibrary.ru/item.asp?id=35434341
15. Al-Ansari Adel, Carlos Parra, Abdullah Abahussain, Amr M. Abuhamed, Rafael Pino, Moustafa El Bialy, HadjSadok Mohamed, Carlos Lopez. Reservoir Drill-In Fluid Minimizes Fluid Invasion and Mitigates Differential Stuck Pipe with Improved Production Test Results. *B Day 3 Wed, March 08, 2017, D031S024R002*. Manama, Kingdom of Bahrain: SPE, 2017. DOI: https://doi.org/10.2118/183764-MS
16. Araujo Ewerton, Darren Kisinger, Daniel Vidal, Barry Cresap. Borehole Stability in Shale: Beyond Mud Weight. *Day 2 Wed, 2020, March 04, D091S009R003*. Galveston, Texas, USA: SPE, 2020. https://doi.org/10.2118/199596-MS
17. Understanding Geological Control on Origin and Distribution of Overpressures Aided in Successful Drilling in a High Pressure High Temperature HPHT Field in South East Asia / Chatterjee Avirup, Amitava Ghosh, Sanjeev Bordoloi, Baker Hughes, A GE Company // International Petroleum Technology Conference. – 2019. DOI: 10.2523/IPTC-19051-MS
18. Allogo C.-M. E., Raymond RAVITZ, Sooi Kim Lim. Monovalent Brine-Based Reservoir Drilling Fluid. United States US20180201820A1, filed 8 July 2016, iss. 19, July 2018, available at: https://patents.google.com/patent/US20180201820A1/en
19. Ale Babajide, Adebowale Oladepo, Adesina Fadairo, Churchill Ako, Ifechukwu Micheals. Effects of Temperature and Pressure on Shale Cuttings Dispersion in Water Based Mud WBM Using NACL, CACL2, KCL Salts as Primary Inhibiting Agents and Polymer XCD Xanthan Gum as Secondary Inhibiting Agent. *All Days. SPE-184310-MS*. Lagos, Nigeria: SPE, 2016. DOI: https://doi.org/10.2118/184310-MS
20. Jia Hu, Cheng-Cheng Niu, Yao-Xi Hu. The Potential Study of Ultra-High Density Heteropolysate Solid Free Brine as Well Completion Fluid for Deep Reservoir Development. *Journal of Natural Gas Science and Engineering*, 2020, vol. 84, 103638 p. DOI: https://doi.org/10.1016/j.jngse.2020.103638
21. Feng Lin, Chang Congbing, Xu Lin, Wang Shengxiang. Study on Experimental Construction of a Novel Brine-Based Drilling Fluid for Salt-Anhydrite Formation. *IOP Conference Series: Earth and Environmental Science*, 2019, vol. 384, 012130 p. DOI: https://doi.org/10.1088/1755-1315/384/1/012130
22. Yurany Villada, Gallardo Felipe, Erdmann Eleonora, Casis Natalia, Olivares Laura, Estenoz Diana. Functional Characterization on Colloidal Suspensions Containing Xanthan Gum (XGD) and Polyanionic Cellulose (PAC) Used in Drilling Fluids for a Shale Formation. *Applied Clay Science*, 2017, vol. 149, pp. 59-66. DOI: https://doi.org/10.1016/j.clay.2017.08.020
23. Salomatov V.A., Kozhaev D.P., Panikarovskii E.V. Primenenie ingibiruiushchego burovogo rastvora dlia podderzhaniia ustoichivosti stenok skvazhiny [Application of inhibiting drilling fluid to maintain the stability of the well walls]. *Bulatovskie chteniia*, 2018, vol 3, pp. 270-281, available at: https://elibrary.ru/item.asp?id=35434371
24. Niall Fleming, Mary Karunakaran, Sammy Hireche. Qualification and Implementation of Oil-Based Mud as a Cost-Effective and Low-Damaging Perforation Fluid for High-Pressure/High-Temperature Fields: Gudrun Case History. *SPE Production & Operations*, 2019, vol. 34(03), pp. 429-45. DOI: https://doi.org/10.2118/189531-PA
25. Li Jiaxue, Qinghui Li, Ning Li, Xueqing Teng, Lingling Ren, Hongtao Liu, Bin Guo, Shaoxuan Li, Nasr-El-Din Hisham, Manayer Al-Mujalhem. Ultra-High Density Oil-Based Drilling Fluids Laboratory Evaluation and Applications in Ultra-HPHT Reservoir. *Day 3 Thu, 2019, October 31, D032S009R010*. Bali, Indonesia: SPE, 2020. DOI: https://doi.org/10.2118/196289-MS
26. Nutskova M.V., Kuchin V.N., Koval'chuk V.S. Profilaktika i likvidatsiia oslozhnenii, voznikaiushchikh pri zakanchivanii skvazhin [Preventing and eliminating well-completion problems]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2020, vol. 20, no. 1. DOI: https://doi.org/10.15593/2224-9923/2020.1.2
27. Rinde T., Killie R., Howard S.K., Solli L., Lillelokken N. Impact of New and Ultra-High Density Kill Fluids on Challenging Well-Kill Operations. *Day 1 Wed, April 20, 2016, D011S004R002*. Grieghallen, Bergen, Norway: SPE, 2016. DOI: https://doi.org/10.2118/180047-MS
28. Li Long, Da Yin, Lei Li, Zihang Yan, Chao Huang, Cha Ma, Yuping Yang, Xiao Liu. Application of Innovative High Density High-Performance Water-Based Drilling Fluid Technology in the Efficient Development and Production of Ultra-Deep Complicated Formations in the Tian Mountain Front Block in China. *Day 4 Fri, March 23, 2018, D041S036R004*. Kuala Lumpur, Malaysia: OTC, 2018. DOI: https://doi.org/10.4043/28413-MS
29. Nekrasova I.L. Aspekty ekologicheskoi i promyshlennoi bezopasnosti primeneniia tekhnologicheskikh zhidkostei na nevodnoi osnove v protsessakh stroitel'stva i osvoeniia skvazhin [Aspects of environmental and industrial safety of non-aqueous process fluids in construction and completion of wells]. *Vestnik permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2018, vol. 18, no. 1. DOI: https://doi.org/10.15593/2224-9923/2018.3.4
30. Pashkevich M.A., Alekseenko A.V., Petrova, T.A. Application of polymeric materials for abating the environmental impact of mine wastes. *J. Phys. Conf. Ser*, 2019, vol. 1384, 012039 p.
31. Nutskova M.V., Sidorov D.A., Tsikplonu D.E., Sergeev G.M., Vasil'ev N.I. Issledovaniia burovykh rastvorov na uglevodorodnoi osnove dlia pervichnogo vskrytiia produktivnykh plastov [Studies of hydgocarbon-based muds for drilling-in productive formations]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2019, vol. 19, no. 2. DOI: https://doi.org/10.15593/2224-9923/2019.2.4
32. Nutskova M.V., Kupavykh K.S., Sidorov D.A., Lundaev V.A. Research of oil-based drilling fluids to improve the quality of wells completion. *IOP Conference Series: Materials Science and Engineering*, 2019, vol. 666(1), 012065. DOI: 10.1088/1757-899X/666/1/012065
33. Galishin R.N., Leusheva E.L. Analiz vliianiia reologicheskikh kharakteristik burovogo rastvora na velichinu ekvivalentnoi tsirkuliatsionnoi plotnosti [Analysis of the influence of the rheological characteristics of the drilling fluid on the value equivalent to the circulating density]. NOVYE IDEI V NAUKAH O ZEMLE: materialy XIV Mezhdunarodnoj nauchno-prakticheskoj konferencii, Moskva, 02–05 aprelya 2019 goda. Moscow, 2019, pp. 232-233.
34. Oney Erge, Van Oort E. Modeling Cuttings Transport and Annular Pack-Off Using Local Fluid Velocities with the Effects of Drillstring Rotation and Eccentricity. *Day 3 Thu, 2020, March 05, D101S019R004*. Galveston, Texas, USA: SPE, 2020. DOI: https://doi.org/10.2118/199587-MS
35. Rami Sindi, Pino Rafael, Gadalla Ahmed, Sharma Sunil. Achievement of Maximum Mud Weights in WBM with Micromax/Barite Blend and Its Successful Implementation in Deep HPHT Challenging Environment. *Day 4 Thu, November 14, 2019, D041S109R004*. Abu Dhabi, UAE: SPE, 2019. DOI: https://doi.org/10.2118/197594-MS
36. Yan Lili, Li Congjun, Zhang Zhilei, Wang Jianhua, Xu Xianguang, Sun Jinsheng, Su Yinao. Successful Application of Unique High-Density Water-Based Drilling Fluid Used in Zhaotong Shale Gas Horizontal Wells. *SPE-176428-MS*. Nusa Dua, Bali, Indonesia: SPE, 2015. DOI: https://doi.org/10.2118/176428-MS

37. Ogorel'tsev V.Iu., Leont'ev S.A., Korotenko V.A., Grachev S.I., Diagilev V.F., Fominykh O.V. Laboratornye issledovaniia vliianiia reologicheskikh kharakteristik sshitykh polimernykh sistem na koeffitsienty pronitsaemosti i vytesneniia nefti [Laboratory study of influence of rheological characteristics of cross-linked polymer systems on permeability and oil displacement coefficients]. *Vestnik permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2020, vol. 20, no. 2. DOI: https://doi.org/10.15593/2224-9923/2020.2.6
38. Zhou Hui, Kay A. Galindo, Weibin Zha. Synergistic Effect of Thermally Stable Polymers for HPHT Brine-Based Drill-in Fluids. *D031S027R002*. Manama, Kingdom of Bahrain: SPE, 2017. DOI: https://doi.org/10.2118/183872-MS
39. Gupta Ambuj. Identification & Development Brine-Based High Temperature - High Pressure Viscosifier Having Thermal Stability for Drilling Completion Fluids, 2019, 9 p.
40. Blinov P.A., Dvoynikov M.V. Rheological and filtration parameters of the polymer salt drilling fluids based on xanthan gum. *J. Eng. Appl. Ences*, 2018, vol. 13, pp. 5661-5664. DOI: 10.36478/jeasci.2018.5661.5664
41. Siv Howard, Kaminski Lauren, Downs John. Xanthan Stability in Formate Brines - Formulating Non-Damaging Fluids for High Temperature Applications. *All Days, SPE-174228-MS*. Budapest, Hungary: SPE, 2015. DOI: https://doi.org/10.2118/174228-MS
42. Zha Weibin, Kay Galindo, Hui Zhou, Jay P. Deville. Thermally Stable Brine-Based Drill-In Fluids. *SPE-174175-MS*. Budapest, Hungary: SPE, 2015. DOI: https://doi.org/10.2118/174175-MS
43. Lomba, Rosana Fatima Teixeira, Rubens Ribeiro Pessanha, Walter Francisco Cardoso Jr, Bruno Lomba, Mauricio Folsta, Jose Thomaz Goncalves, Gleber T. Teixeira. Lessons Learned in Drilling Pre-Salt Wells With Water Based Muds. *All Days, OTC-24355-MS*. Rio de Janeiro, Brazil: OTC, 2013. DOI: https://doi.org/10.4043/24355-MS
44. Onu Ogbonnaya Victor, Ohenhen Ikponmwosa. Antimony Sulphide Stibnite and Potash as Local Substitute to Barite and Lignosulfonate as Drilling Mud Weighting Additives. *All Days, SPE-172407-MS*. Lagos, Nigeria: SPE, 2014. DOI: https://doi.org/10.2118/172407-MS
45. Zhivaeva V.V., Nozhkina O.V., Kapitonov V.A. Razrabotka retseptur utiazhelennykh vysokomineralizovannykh burovykh rastvorov i opredelenie ikh korrozionnoi aktivnosti [Designing the recipe of weighted high-mineralized drill mud and defining their corrosion activity]. *Neft'. Gaz. Novatsii*, 2020, iss. 1(230), pp. 29-33, available at: https://elibrary.ru/item.asp?id=42485083
46. Litvinenko Vladimir S., Nikolaev N.I. Development of the weighted biopolimer drilling mud for workover. *Journal of Mining Institute*, 2012, vol. 199, 375 p.
47. Raupov I.R., Shagiakhmetov A.M. The results of the complex rheological studies of the cross-linked polymer composition and the grounding of its injection volume. *International Journal of Civil Engineering and Technology*, 2019, vol. 10(2), pp. 493-509.

Библиографический список

1. Alternative High Density Brines / Champeau Mathieu, Xia Wei, Phillip Jackson, Changping Sui, Joyce Zhang, Albert Okhrimenko // SPE Offshore Europe Conference and Exhibition. – 2019. – September 04. – D021S009R007. – Aberdeen, UK: SPE, 2019. DOI: https://doi.org/10.2118/195743-MS
2. Zhou Hui, Deville Jay P., Chesnee L. Davis. Novel High Density Brine-Based Drill-In Fluids Significantly Increased Temperature Limit for HP/HT Applications // D012S020R003. – London, England, UK: SPE, 2015. DOI: https://doi.org/10.2118/173075-MS
3. Fattah K.A., Lashin A. Investigation of Mud Density and Weighting Materials Effect on Drilling Fluid Filter Cake Properties and Formation Damage // Journal of African Earth Sciences. – 2016. – Vol. 117. – P. 345–57. DOI: https://doi.org/10.1016/j.jafrearsci.2016.02.003
4. Paradigm Shift in Reducing Formation Damage: Application of Potassium Formate Water Based Mud in Deep HPHT Exploratory Well / Al-salali, Yousef Zaid, Haifa Al-Bader, D. Vidyasagar, A. Manimaran, S. Packirisamy, Abdulla Al-Ibrahim // SPE-163301-MS. – Kuwait City, Kuwait: SPE, 2012. – Vol. 1, 2. DOI: https://doi.org/10.2118/163301-MS
5. Sukhoboka O. Drilling Fluid Rheology Under High Pressure High Temperature Conditions and Its Impact on the Rate of Penetration // Proceedings of the Nigeria Annual International Conference and Exhibition, April 05. 2017, D011S003R001. – Bergen, Norway: SPE, 2017. DOI: https://doi.org/10.2118/185916-MS
6. High Density Drilling Fluids for Managed Pressure Drilling / Wagle Vikrant, Abdullah S. Al-Yami, Mohammad Aljubran, Hussain Al-Bahrani // SPE-192248-MS. – Dammam, Saudi Arabia: SPE, 2018. DOI: https://doi.org/10.2118/192248-MS
7. Чаяндинское месторождение – проект внедрения новых технологий в Восточной Сибири» / А.В. Давыдов, А.В. Погрецкий, О.А. Смирнов, А.В. Лукашов, А.П. Правдухин, А.Р. Курчиков, В.Н. Бородкин // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2017. – Т. 16, № 2. DOI: https://doi.org/10.15593/2224-9923/2017.2.2
8. Moradi S.S.T., Nikolaev N.I., Chudinova I.V. Geomechanical Analysis of Wellbore Stability in High-pressure, High-temperature Formations // Proceedings of the Eage Conference & Exhibition. – Paris, France, 2017. DOI: 10.3997/2214-4609.201701463
9. Geomechanical study of well stability in high-pressure, high-temperature conditions / S.S.T. Moradi, N.I. Nikolaev, I.V. Chudinova, A.S. Martel // Geomechanics and Engineering. – 2018. – Vol. 16 (3). – P. 331–339. DOI: 10.12989/gae.2018.16.3.331
10. On the Mechanisms of the Formation of Zones with Abnormally High Rock Pressure and Methods for Predicting Them in Undeveloped Rock Systems / A. Islamov, D. Kolupaev, R. Faskhutdinov, S. Vereschagin // SPE Russian Petroleum Technology Conference. – 2018. – October 16. – Moscow, Russia: SPE, 2018. DOI: https://doi.org/10.2118/191501-18RPTC-MS
11. Dvoynikov M.V., Kuchin V.N., Mintzaev M.Sh. Development of viscoelastic systems and technologies for isolating water-bearing horizons with abnormal formation pressures during oil and gas wells drilling // Journal of Mining Institute. – 2021. – Vol. 247. – P. 1–9. DOI: 10.31897/PMI.2021.1.7
12. Ильин И.А. Модель внутрисолевых рапонасыщенных пластов, осложняющих процесс бурения скважин Астраханского ГКМ // Газовая промышленность. – 2020. – Вып. 4 (799). – URL: https://elibrary.ru/item.asp?id=43812968.
13. Ilinova A., Chanysheva A. Algorithm for assessing the prospects of offshore oil and gas projects in the Arctic // Energy Reports. – 2020. – Vol. 6. – P. 504–509. DOI:10.1016/j.egyr.2019.11.110
14. Махаматхожаев Д.Р., Ёкубова Ф.Б., Саидов Т.С. Бурения скважин в соленосных отложениях АО «Узбурнефтегаз» в условиях рапопроявления [Электронный ресурс] // Булатовские чтения 3 (2018 г.). – URL: https://elibrary.ru/item.asp?id=35434341 (дата обращения: 15.08.2020).
15. Reservoir Drill-In Fluid Minimizes Fluid Invasion and Mitigates Differential Stuck Pipe with Improved Production Test Results / Al-Ansari Adel, Carlos Parra, Abdullah Abahussain, Amr M. Abuhamed, Rafael Pino, Moustafa El Bialy, HadjSadok Mohamed, Carlos Lopez // Society of Petroleum Engineers (SPE), March 08, 2017, D031S024R002. – Manama, Kingdom of Bahrain: SPE, 2017. DOI: https://doi.org/10.2118/183764-MS
16. Araujo Ewerton, Darren Kisinger, Daniel Vidal, Barry Cresap. Borehole Stability in Shale: Beyond Mud Weight // SPE, March 04 2020. – D091S009R003. – Galveston, Texas, USA: SPE, 2020. https://doi.org/10.2118/199596-MS.
17. Understanding Geological Control on Origin and Distribution of Overpressures Aided in Successful Drilling in a High Pressure High Temperature HPHT Field in South East Asia / Chatterjee Avirup, Amitava Ghosh, Sanjeev Bordoloi, Baker Hughes, A GE Company // International Petroleum Technology Conference. – 2019. DOI: 10.2523/IPTC-19051-MS
18. Allogo C.-M. E., Raymond RAVITZ, Sooi Kim Lim. Monovalent Brine-Based Reservoir Drilling Fluid: pat. United States US20180201820A1. – 2016, issued 2018.
19. Effects of Temperature and Pressure on Shale Cuttings Dispersion in Water Based Mud WBM Using NACL, CACL2, KCL Salts as Primary Inhibiting Agents and Polymer XCD Xanthan Gum as Secondary Inhibiting Agent / Babajide Ale, Oladepo Adebowale, Fadairo Adesina, Ako Churchill, Micheals Ifechukwu // SPE-184310-MS. – Lagos, Nigeria: SPE, 2016. DOI: https://doi.org/10.2118/184310-MS
20. Jia Hu, Cheng-Cheng Niu, Yao-Xi Hu. The Potential Study of Ultra-High Density Heteropolysate Solid Free Brine as Well Completion Fluid for Deep Reservoir Development // Journal of Natural Gas Science and Engineering. – 2020. – Vol. 84. – P. 103638. DOI: https://doi.org/10.1016/j.jngse.2020.103638
21. Study on Experimental Construction of a Novel Brine-Based Drilling Fluid for Salt-Anhydrite Formation / Lin Feng, Congbing Chang, Lin Xu, Shengxiang Wang // IOP Conference Series: Earth and Environmental Science. – 2019. – Vol. 384. – P. 012130. DOI: https://doi.org/10.1088/1755-1315/384/1/012130
22. Functional Characterization on Colloidal Suspensions Containing Xanthan Gum (XGD) and Polyanionic Cellulose (PAC) Used in Drilling Fluids for a Shale Formation / Villada Yurany, Felipe Gallardo, Eleonora Erdmann, Natalia Casis, Laura Olivares, Diana Estenoz // Applied Clay Science. – 2017. – Vol. 149. – P. 59–66. DOI: https://doi.org/10.1016/j.clay.2017.08.020
23. Саломатов В.А., Кожаев Д.П., Паникаровский Е.В. Применение ингибирующего бурового раствора для поддержания устойчивости стенок скважины [Электронный ресурс] // Булатовские чтения 3 (2018 г.). – URL: https://elibrary.ru/item.asp?id=35434371 (дата обращения: 15.08.2021).
24. Fleming N., Karunakaran M., Hireche S. Qualification and Implementation of Oil-Based Mud as a Cost-Effective and Low-Damaging Perforation Fluid for High-Pressure/High-Temperature Fields: Gudrun Case History // SPE Production & Operations. – 2019. – Vol. 34 (03). – P. 429–45. DOI: https://doi.org/10.2118/189531-PA
25. Ultra-High Density Oil-Based Drilling Fluids Laboratory Evaluation and Applications in Ultra-HPHT Reservoir / Li Jiaxue, Qinghui Li, Ning Li, Xueqing Teng, Lingling Ren, Hongtao Liu, Bin Guo, Shaoxuan Li, Nasr-El-Din Hisham, Manayer Al-Mujalhem // SPE/IATMI Asia Pacific Oil & Gas Conference. – 2019. – October 31. – D032S009R010. – Bali, Indonesia: SPE, 2020. DOI: https://doi.org/10.2118/196289-MS
26. Нуцкова М.В., Кучин В.Н., Ковальчук В.С. Профилактика и ликвидация осложнений, возникающих при заканчивании скважин // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2020. – Т. 20, № 1. DOI: https://doi.org/10.15593/2224-9923/2020.1.2
27. Impact of New and Ultra-High Density Kill Fluids on Challenging Well-Kill Operations / T. Rinde, R. Killie, S.K. Howard, L. Solli, N. Lillelokken // SPE/IATMI Asia Pacific Oil & Gas Conference, April 20, 2016, D011S004R002. – Grieghallen, Bergen, Norway: SPE, 2016. DOI: https://doi.org/10.2118/180047-MS
28. Application of Innovative High Density High-Performance Water-Based Drilling Fluid Technology in the Efficient Development and Production of Ultra-Deep Complicated Formations in the Tian Mountain Front Block in China / Long Li, Yin Da, Li Lei, Yan Zihang, Huang Chao, Ma Cha, Yang Yuping, Liu Xiao // SPE/IATMI Asia Pacific Oil & Gas Conference, March 23, 2018, D041S036R004. – Kuala Lumpur, Malaysia: OTC, 2018. DOI: https://doi.org/10.4043/28413-MS
29. Некрасова И.Л. Аспекты экологической и промышленной безопасности применения технологических жидкостей на неводной основе в процессах строительства и освоения скважин // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2018. – Т. 18, № 1. DOI: https://doi.org/10.15593/2224-9923/2018.3.4
30. Pashkevich M.A., Alekseenko A.V., Petrova, T.A. Application of polymeric materials for abating the environmental impact of mine wastes // J. Phys. Conf. Ser. – 2019. – Vol. 1384. – P. 012039.
31. Исследования буровых растворов на углеводородной основе для первичного вскрытия продуктивных пластов / М.В. Нуцкова, Д.А. Сидоров, Д.Э. Тсикплону, Г.М. Сергеев, Н.И. Васильев // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2019. – Т. 19, № 2. DOI: https://doi.org/10.15593/2224-9923/2019.2.4
32. Research of oil-based drilling fluids to improve the quality of wells completion / M.V. Nutskova, K.S. Kupavykh, D.A. Sidorov, V.A. Lundaev // IOP Conference Series: Materials Science and Engineering. – 2019. – Vol. 666 (1). – P. 012065. DOI: 10.1088/1757-899X/666/1/012065
33. Галишин Р.Н., Леушева Е.Л. Анализ влияния реологических характеристик бурового раствора на величину, эквивалентную циркуляционной плотности // НОВЫЕ ИДЕИ В НАУКАХ О ЗЕМЛЕ: материалы XIV Междунар. науч.-практ. конф., Москва, 02–05 апреля 2019 г. – М., 2019. – С. 232–233.
34. Oney Erge, Van Oort E. Modeling Cuttings Transport and Annular Pack-Off Using Local Fluid Velocities with the Effects of Drillstring Rotation and Eccentricity // SPE/EPA Exploration and Production Environmental Conference. – 2020. – March 05. – D101S019R004. – Galveston, Texas, USA: SPE, 2020. DOI: https://doi.org/10.2118/199587-MS
35. Achievement of Maximum Mud Weights in WBM with Micromax/Barite Blend and Its Successful Implementation in Deep HPHT Challenging Environment / Sindi Rami, Rafael Pino, Ahmed Gadalla, Sunil Sharma // International Petroleum Conference, November 14, 2019, D041S109R004. – Abu Dhabi, UAE: SPE, 2019. DOI: https://doi.org/10.2118/197594-MS
36. Successful Application of Unique High-Density Water-Based Drilling Fluid Used in Zhaotong Shale Gas Horizontal Wells / Yan Lili, Congjun Li, Zhilei Zhang, Jianhua Wang, Xianguang Xu, Jinsheng Sun, Yinao Su // SPE-176428-MS. – Nusa Dua, Bali, Indonesia: SPE, 2015. DOI: https://doi.org/10.2118/176428-MS
37. Лабораторные исследования влияния реологических характеристик сшитых полимерных систем на коэффициенты проницаемости и вытеснения нефти / В.Ю. Огорельцев, С.А. Леонтьев, В.А. Коротенко, С.И. Грачев, В.Ф. Дягилев, О.В. Фоминых // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2020. – Т. 20, № 2. DOI: https://doi.org/10.15593/2224-9923/2020.2.6
38. Zhou Hui, Kay A. Galindo, Weibin Zha. Synergistic Effect of Thermally Stable Polymers for HPHT Brine-Based Drill-in Fluids // SPE Middle East Oil & Gas Show and Conference. D031S027R002. – Manama, Kingdom of Bahrain: SPE, 2017. DOI: https://doi.org/10.2118/183872-MS
39. Gupta Ambuj. Identification & Development Brine-Based High Temperature - High Pressure Viscosifier Having Thermal Stability for Drilling Completion Fluids // International Journal of Computational Science and Engineering. – 2019. – April. – P. 9.
40. Blinov P.A., Dvoynikov M.V. Rheological and filtration parameters of the polymer salt drilling fluids based on xanthan gum // J. Eng. Appl. Ences. – 2018. – Vol. 13. – P. 5661–5664. DOI: 10.36478/jeasci.2018.5661.5664
41. Siv Howard, Kaminski Lauren, Downs John. Xanthan Stability in Formate Brines - Formulating Non-Damaging Fluids for High Temperature Applications // SPE-174228-MS. – Budapest, Hungary: SPE, 2015. DOI: https://doi.org/10.2118/174228-MS
42. Thermally Stable Brine-Based Drill-In Fluids / Zha Weibin, Kay Galindo, Hui Zhou, Jay P. Deville // SPE-174175-MS. – Budapest, Hungary: SPE, 2015. DOI: https://doi.org/10.2118/174175-MS
43. Lessons Learned in Drilling Pre-Salt Wells With Water Based Muds / Lomba, Rosana Fatima Teixeira, Rubens Ribeiro Pessanha, Walter Francisco Cardoso Jr, Bruno Lomba, Mauricio Folsta, Jose Thomaz Goncalves, Gleber T. Teixeira // OTC-24355-MS. – Rio de Janeiro, Brazil: OTC, 2013. DOI: https://doi.org/10.4043/24355-MS
44. Onu Ogbonnaya Victor, Ohenhen Ikponmwosa. Antimony Sulphide Stibnite and Potash as Local Substitute to Barite and Lignosulfonate as Drilling Mud Weighting Additives // SPE-172407-MS. – Lagos, Nigeria: SPE, 2014. DOI: https://doi.org/10.2118/172407-MS
45. Живаева В.В., Ножкина О.В., Капитонов В.А. Разработка рецептур утяжеленных высокоминерализованных буровых растворов и определение их коррозионной активности // Нефть. Газ. Новации. – 2020. – Вып. 1 (230). – С. 29–33.
46. Litvinenko Vladimir S., Nikolaev N.I. Development of the weighted biopolimer drilling mud for workover // Journal of Mining Institute. – 2012. – Vol. 199. – P. 375.
47. Raupov I.R., Shagiakhmetov A.M. The results of the complex rheological studies of the cross-linked polymer composition and the grounding of its injection volume // International Journal of Civil Engineering and Technology. – 2019. – Vol. 10 (2). – P. 493–509.