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Review article

Spacer Fluids for Wells Drilled with Invert Emulsion Drilling Fluids: A Review of Their Role in Preventing Formation Damage

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ABSTRACT
This article examines problems associated with the quality of cementing and casing integrity in oil and gas wells under conditions of increasing drilling activity in Kazakhstan. It is shown that complications such as behind-casing hydrocarbon migration, sustained casing pressure, and water coning are largely caused by poor cementing quality and the loss of wellbore integrity. It is noted that more than 30% of wells worldwide exhibit inter-casing pressures of varying intensity, which highlights the relevance and significance of this issue. The main causes of cement sheath degradation under the influence of mechanical, hydraulic, and thermal loads during well operation are analyzed. Particular attention is given to the problem of incomplete displacement of drilling fluids in the annular space, which leads to channel formation and a reduction in the isolation properties of the cement sheath. The role of buffer fluids in the cementing of wells drilled with hydrocarbon-based drilling fluids is also considered. The study emphasizes the need to develop effective buffer systems that ensure compatibility between drilling fluids and cement slurries, thereby improving displacement efficiency and enhancing the overall quality of well cementing and zonal isolation.

Keywords: *well cementing; wellbore integrity; inter-casing pressure; behind-casing hydrocarbon migration; cement sheath; spacer fluids; oil-based drilling fluids; zonal isolation.*

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Научный обзор

Буферные жидкости при бурении инвертно-эмульсионными растворами: обзор и влияние на загрязнение продуктивного пласта

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АННОТАЦИЯ
В статье рассмотрены проблемы, связанные с качеством цементирования и крепления нефтяных и газовых скважин в условиях роста объёмов буровых работ в Казахстане. Показано, что такие осложнения, как заколонная миграция углеводородов, межколонные давления и образование конусов воды, в значительной степени обусловлены некачественным цементированием и нарушением герметичности крепи скважин. Отмечено, что более 30% скважин в мире имеют межколонные давления различной интенсивности, что подтверждает актуальность данной проблемы. Проанализированы основные причины разрушения тампонажного камня под воздействием механических, гидравлических и температурных нагрузок в процессе эксплуатации скважин. Особое внимание уделено вопросам неполного вытеснения бурового раствора в кольцевом пространстве, приводящего к образованию каналов и снижению изоляционных свойств цементного камня. Рассмотрена роль буферных жидкостей при цементировании скважин, пробуренных растворами на углеводородной основе, и показана необходимость разработки эффективных буферных систем, обеспечивающих совместимость буровых и тампонажных растворов и повышение качества крепления скважин.
Ключевые слова: *цементирование скважин, целостность ствола скважины, межколонное давление, заколонная миграция углеводородов, цементный камень, буферные жидкости, буровые растворы на углеводородной основе, изоляция пластов.*

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Ғылыми шолу

Инвертті эмульсиялық ерітінділермен бұрғылау кезіндегі буферлік сұйықтықтар: шолу және өнімді қабаттың ластануына әсері

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АҢДАТПА
Қазақстанда бұрғылау жұмыстары көлемінің артуы жағдайында мұнай және газ ұңғымаларын цементтеу және бекіту сапасына байланысты мәселелер аталған мақалада қарастырылған. Көмірсутектердің колонна сыртындағы көшіп-қонуы, бағанаралық қысым және су конустарының пайда болуы сияқты асқынулар негізінен сапасыз цементтеу мен ұңғымалар бекіткіштерінің герметикалығының бұзылуына байланысты екендігі көрсетілген. Әлемдегі ұңғымалардың 30%-дан астамында әртүрлі қарқындылықтағы бағанаралық қысымдар бар, бұл осы мәселенің өзектілігін растайды. Ұңғымаларды пайдалану процесінде механикалық, гидравликалық және температуралық жүктемелердің әсерінен тампонаждық тастың бұзылуының негізгі себептері талданды. Арналардың пайда болуына және цемент тастың оқшаулау қасиеттерінің төмендеуіне әкелетін сақиналы кеңістіктегі бұрғылау ерітіндісінің толық ығыстырылмау мәселелеріне ерекше назар аударылады. Көмірсутек негізіндегі ерітінділермен бұрғыланған ұңғымаларды цементтеу кезінде буферлік сұйықтықтардың рөлі қарастырылып, бұрғылау және тампонаждық ерітінділердің үйлесімділігін қамтамасыз ететін әрі ұңғымаларды бекіту сапасын арттыратын тиімді буферлік жүйелерді әзірлеу қажеттілігі көрсетілді.
Негізгі сөздер: *ұңғымаларды цементтеу, ұңғыма оқпанының тұтастығы, бағанааралық қысым, колонна сыртындағы көмірсутектердің көшіп-қонуы, цемент тасы, буферлік сұйықтықтар, көмірсутек негізіндегі бұрғылау ерітінділері, қабаттарды оқшаулау.*

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Introduction

Hydrocarbon drilling activities in Kazakhstan have increased with the discovery of new hydrocarbon deposits (e.g., Klimene and Khalel Uzbekgaliyev) and the expansion of exploration and appraisal operations, which has consequently led to a growth in well construction and cementing activities [1]. However, several production challenges in many oil fields of Kazakhstan—such as behind-casing hydrocarbon migration and water coning—remain unresolved. These problems are closely related to the technical condition of wells and the quality of well completion [2]. According to various studies, approximately one quarter of oil and gas wells worldwide experience inter-casing pressure of varying intensity [3, 4]. These data highlight the importance and relevance of improving well completion quality and developing advanced cementing materials to ensure reliable casing integrity in oil and gas wells.

A considerable number of studies have been conducted to address the problem of inter-casing pressure and fluid crossflows in oil and gas wells. However, this issue remains relevant not only in Kazakhstan but also worldwide [5, 6]. Measures aimed at eliminating poor zonal isolation associated with inter-casing flows typically involve shutting in the operating well and using kill fluids, which may negatively affect well productivity. In addition, remedial operations require significant time and financial resources [5, 6–8].

Gas migration, inter-casing pressure, and behind-casing fluid flows are often the result of poor-quality cementing, which requires careful attention during the selection and design of cement slurry systems. The proper formulation of cement slurries is therefore critically important.

Materials and Methods

This study employed a method of analytical review of the scientific and technical literature devoted to the application of buffer fluids in wells drilled using invert emulsion drilling fluids.

The information sources included publications indexed in international and national databases, including Scopus, Web of Science, Google Scholar, and eLIBRARY, as well as conference proceedings and industry reports.

The literature was selected using the following keywords: "spacers," "invert emulsion drilling fluids," "formation damage," and "wellbore cleaning." The analysis included studies published primarily during the period from 2010 to 2025, reflecting contemporary approaches to the use of buffer fluids.

The study applied comparative and systems analysis methods, as well as data synthesis, to identify the main patterns governing the influence of buffer fluids on productive formation damage.

Literature review

The primary objective of well cementing is to create a hermetic wellbore barrier that maintains its integrity throughout the entire operational life of the well. If the integrity of the wellbore is compromised, particularly in the productive formation interval, subsequent well stimulation methods aimed at improving well productivity may become ineffective.

Unfortunately, after hardening, the cement sheath is subjected to various mechanical and thermal loads that may lead to cracking and, consequently, to the loss of wellbore integrity. Such loads may occur during drilling operations when drill bits and drilling tools impact the casing walls while drilling out the cement plug and during subsequent deepening of the well; during casing running; during casing pressure testing; during well perforation; and during hydraulic fracturing operations. In addition, thermal loads may arise during cement hydration, thermal cycling of formations, and during the injection of steam, hot water, or cold water into the reservoir [12]. These stresses inevitably contribute to the formation of cracks in the cement sheath, particularly across the productive interval. As illustrated in Fig. 1, potential pathways for fluid migration include the formation of microannuli between the casing and the cement sheath (Fig. 1, b), channels within the cement sheath (Fig. 1, c), fractures and damaged zones in the cement matrix (Fig. 1, d and e), and gaps between the cement sheath and the surrounding formation (Fig. 1, b). In addition, Fig. 1 also demonstrates possible leakage and migration pathways relevant to well abandonment and decommissioning operations (Fig. 1, a and c).

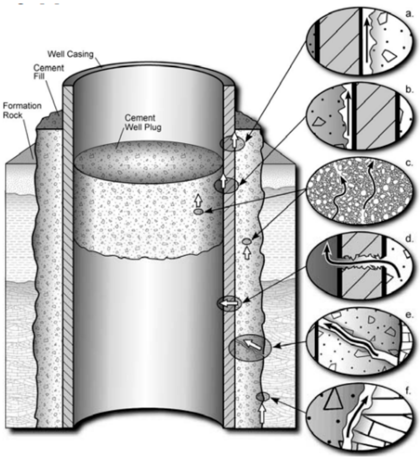

Figure 1. Schematic representation of potential leakage pathways along the wellbore

a) between the cement and the outer surface of the casing; b) between the cement and the inner surface of the casing; c) through the cement sheath; d) through the casing; e) through cracks in the cement; f) between the cement and the formation

Undoubtedly, these loads can lead to the formation of cracks in the cement sheath, particularly in the productive formation interval. The consequences of this problem include gas migration, inter-casing pressure, and a decrease in the effectiveness of enhanced oil and gas recovery methods. It is estimated that inter-casing pressure occurs in more than 30% of wells worldwide. Furthermore, the complexity of this issue is associated with the inaccessibility of such cracks, which significantly complicates subsequent well repair operations or secondary cementing.

Many researchers focus in their studies on the proper selection of cement slurry formulations and on the cementing process after slurry placement. However, it is also important to emphasize the significance of efficient displacement and pre-circulation prior to cement slurry placement (Fig. 2) [10].

During pre-cementing circulation, drilling fluid remains in the annular space and is subsequently displaced by spacer fluids and cement slurry. However, two main problems may arise during this circulation process. The first problem is related to complications caused by the incompatibility of technological fluids, which can lead to loss of circulation [10]. The second problem is the incomplete displacement of drilling fluid, which may result in the absence of cement sheath behind the casing and the formation of channels between the cement and the casing or between the cement sheath and the formation.

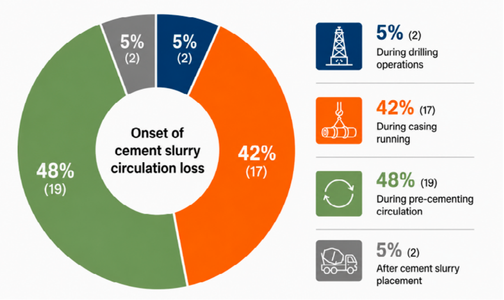

Figure 2. Onset of cement slurry circulation loss [10]

If cement slurries are incompatible with drilling fluids [11], contact between the cement slurry and the drilling fluid may lead to the formation of a highly viscous mass that prevents further displacement of fluids in the annular space. As a result, operational problems may occur, including accidents or incomplete cement slurry placement in the annulus up to the required height. To prevent such problems, preliminary flushing using intermediate fluids, commonly referred to as spacer fluids, is applied [12]. As intermediate fluids, chemical solutions that do not contain suspended solids may be used, as well as spacer fluids containing solid additives mixed to achieve different densities.

If drilling fluids were fully compatible with cement slurries, the use of spacer fluids could potentially be avoided [11]. Studies conducted by several authors in this area have reported positive results [13–15]. However, drilling fluids may be either water-based or hydrocarbon-based, which are often incompatible with cement slurries and conventional spacer fluids. Despite their advantages in preserving the reservoir properties of productive formations and their promising application in drilling operations, oil-based drilling fluids present additional challenges. In particular, they tend to form a film or filter cake on the wellbore surface, which reduces the adhesion of the cement sheath to the surrounding surfaces. As a result, the use of effective spacer fluids becomes essential when oil-based drilling fluids are employed [16–17].

Oil-based drilling fluids consist of oil as the continuous phase and water as the dispersed phase, combined with emulsifiers, wetting agents, and gelling agents. Various hydrocarbon liquids may be used as the oil phase, including diesel fuel, kerosene, fuel oil, selected crude oil, or mineral oil; however, in practice diesel or kerosene are most commonly used [12]. Such drilling fluids are characterized by high drilling rates, reduced torque and drag on the drill string, and a lower risk of differential sticking. This type of drilling fluid can also be used as a completion and workover fluid, as a spotting fluid for freeing stuck pipe, and as a packer or casing fluid. Oil-based drilling fluids are particularly effective when drilling reactive shale formations, such as “gumbo” shales.

The density of the drilling fluid can be adjusted within the range of approximately 7–22 lb/gal. Although these fluids are sensitive to temperature, they do not undergo dehydration as water-based drilling fluids do. They also do not have strict limitations on the concentration of drilled solids. The water phase should be maintained at a pH above 7, and the stability of the emulsion depends on the alkalinity of the system [18]. Oil-based drilling fluids are also commonly referred to as invert emulsion drilling fluids. In such systems, the dispersed phase typically consists of an aqueous solution containing various salts to maintain wellbore stability during drilling. Surfactants are used to ensure the stability of the emulsion.

The aqueous phase typically contains highly concentrated salts, such as calcium chloride or calcium hydroxide. When in contact with cement slurry, the salts present in the aqueous phase of the drilling fluid may accelerate the cement setting process. In contrast, emulsifiers may have the opposite effect, as they can adsorb onto the surface of cement particles and thereby prolong the hydration process [20]. The compatibility of invert emulsion drilling fluids with cement slurries may also depend on the composition of the cement system itself [21]. Therefore, analysis of these factors indicates that invert emulsion drilling fluids exhibit more complex and generally less effective compatibility with cement slurries compared with water-based drilling fluids [12].

Another advantage of oil-based drilling fluids is the lower friction within the wellbore. Therefore, they are often used in extended-reach wells, where friction becomes a critical parameter. In contrast to water-based fluids, significant deterioration of drill-

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ing fluid properties over time is typically not observed when oil-based systems are used. In addition, capillary pressure prevents the penetration of oil into water-wet formations [16].

In addition to the excellent filter-cake–forming properties of oil-based drilling fluids, when properly formulated their use can minimize the risk of disturbing the natural inflow conditions of productive formations.

Oil-based drilling fluids are particularly effective when drilling through formations such as highly reactive shales, where water wetting can cause significant operational difficulties. They also allow core samples to be obtained without contamination by drilling water. These fluids act as the liquid medium of the system, control viscosity, contribute to the development of initial and final gel strengths, provide gel structure and stability to prevent particle settling, and can serve as a weighting medium in the drilling fluid system [17].

Another challenge is poor displacement efficiency. For example, polymer-based drilling fluids are commonly used to reduce fluid loss; however, these fluids are more difficult to displace from the annular space compared with bentonite-based drilling fluids. Invert emulsion drilling fluids contain emulsifiers and surfactants that can adsorb onto the surfaces of minerals and form a coating over the entire surface. If poor displacement leads to various problems associated with inadequate cementing, the situation becomes even more complicated when invert emulsion drilling fluids are used, since the cement may not properly adhere to the casing surface [19]. Therefore, the study and development of effective spacer fluids for wells drilled with invert emulsion drilling fluids is of great importance and remains a highly relevant research topic.

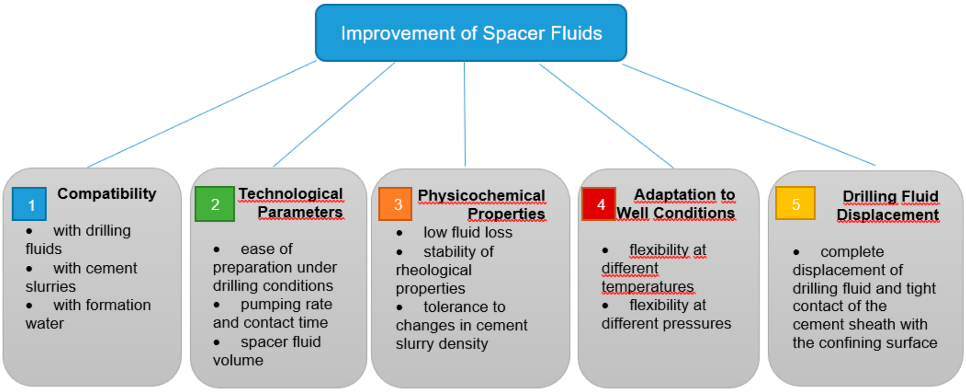

Figure 3. Main criteria for the improvement of spacer fluids

The authors of study [22] identified, in addition to compatibility and the degree of casing and wellbore cleaning, several key indicators of spacer fluid performance. These include the stability of rheological properties, pumping rate and contact time, and the volume of the spacer fluid.

Various approaches have been proposed for the development of effective spacer fluids. However, among these approaches, the investigation of the cleaning and filter-cake removal properties of developed spacer systems remains insufficiently studied. Therefore, the development of effective spacer fluids for cementing wells drilled with oil-based drilling fluids, based on studying the mechanisms of interaction between the hydrocarbon components of the drilling fluid and both the formation and casing surfaces, as well as investigating the cleaning and filter-cake removal capabilities of the developed spacer systems, represents a novel research direction.

However, reservoir contamination remains a significant concern. For example, the study of reservoir permeability recovery after interaction with mixtures of technological fluids is very important during primary cementing. Primary cementing is the process of placing cement slurry in the annular space between the casing and the wellbore wall. After placement, the cement slurry hardens into a solid cement sheath that prevents migration of formation fluids and provides reliable zonal isolation. Therefore, primary cementing is a critically important stage in well construction, as there is typically only one opportunity to perform this operation successfully [23].

High-quality well cementing, particularly during well completion, is critically important, since in addition to ensuring reliable wellbore isolation it is also necessary to prevent contamination of the productive formation. Reservoir contamination refers to the sequential invasion of technological fluids such as drilling fluids, spacer fluids, and cement slurries into the formation. Many researchers indicate that drilling fluids are the primary type of technological fluid responsible for reservoir contamination and have the most significant negative impact on the filtration and reservoir properties of productive formations [24]. However, it should also be noted that the fluid loss of cement slurries could be up to ten times greater than that of drilling fluids [25, 26]. The filtrate of cement slurry can penetrate into the productive formation to depths of up to 10 meters. Consequently, cement slurry filtrate can affect not only the efficiency of subsequent operations such as well perforation and well clean-up, but also the overall well productivity. For example, earlier studies conducted by N.Kh. Karimov and F.A. Agzamov on core samples demonstrated that the permeability recovery coefficient of the cores did not exceed 60% [25, 26].

Undoubtedly, the productive formation may also be damaged during secondary reservoir exposure due to the contaminating effects of filtrates from perforation fluids [24–27]. However, reducing the impact of cement slurry filtrate on reservoir contamination is also important for several reasons. The fluid loss of cement slurries is generally higher than that of drilling fluids, and the filtrate of cement slurry can significantly affect the permeability of the near-wellbore zone as well as the effectiveness of secondary reservoir exposure operations.

The main causes of reservoir impairment are considered to be the following [24, 28]:

– swelling of clay particles;

– formation of emulsions;

– high interfacial tension at the filtrate–formation fluid interface;

– chemical interactions between the filtrate and formation fluids, as well as between different filtrates.

The latter leads to pore plugging in reservoir rocks as a result of the supersaturation of formation water with salts originating from the filtrate [29], as well as to changes in rheological properties. Pore blockage may also occur due to the penetration of solid particles from the cement slurry into the pore space [29]. In addition, cement slurries may contain insoluble salts such as $CaCO_3$ and $CaSO_4$. Cement slurries typically exhibit a higher pH compared with drilling fluids. Under such conditions, clay and other fine rock particles may detach from the formation matrix and migrate through the reservoir, potentially causing pore plugging [30]. This phenomenon may influence experimental results, which necessitates the use of core samples that have been pre-cleaned of clay particles. A review of the literature shows that many researchers have conducted experiments in this area [28–30]. However, the relevance and necessity of further investigation are increasing due to the fact that modern cement slurry formulations include a wide range of additives such as expanding agents, plasticizers, accelerators and retarders, fluid-loss reducers, defoamers, anti-settling additives for lightweight materials, fibers, and other chemical reagents that serve as regulators of technological properties [30]. Nevertheless, many developed cement slurry systems also exhibit undesirable effects that may lead to contamination of productive formations.

In field practice, various technologies are applied to reduce or prevent contamination of the near-wellbore zone of the reservoir, such as underbalanced drilling and the use of oil-based drilling fluids. However, underbalanced drilling is a relatively complex process to implement, and well cementing operations are still performed using conventional methods. The use of oil-based drilling fluids is considered a less damaging technology for reservoir protection; however, their high cost, increased operational risks, and other factors impose certain limitations on their application [28]. Therefore, it is necessary to take into account the composition and compatibility of technological fluids with formation water and the reservoir rock of productive formations.

Results

The analysis of the literature demonstrated that buffer fluids play a key role in ensuring an effective transition from drilling fluids to completion fluids during the exposure of productive formations.

Based on the above-mentioned materials, it can be concluded that the improvement of spacer fluids should be guided by several key criteria [12] (Fig. 3):

– compatibility of the spacer fluid with various drilling fluids;

– compatibility of the spacer fluid with different cement slurries;

– complete displacement of drilling fluids and ensuring tight contact between the cement sheath and the confining surface;

– tolerance to variations in cement slurry density;

– adaptability to different temperatures and pressures;

– ease of preparation under drilling conditions;

– low fluid loss;

– stability of rheological properties [22];

– pumping rate and contact time [22];

– spacer fluid volume [22].

The relevance of studying spacer fluids for wells drilled with invert emulsion drilling fluids and their relationship with reservoir contamination lies in the possibility of utilizing the anomalous behavior of dispersed systems to prevent filtrate penetration into productive formations. This involves identifying non-Newtonian and filtration anomalies of filtrates from drilling, spacer, and cementing fluids in porous media containing microscale channels, with the aim of limiting fluid loss and predicting contamination of the near-wellbore zone of productive formations. Such studies are based on investigating the mechanisms of interaction between filtrates of technological fluids, rock-forming minerals, and polymeric reagents, as well as examining the conditions of filtrate flow through pores of different sizes. In addition, predictive evaluation of the depth of filtrate penetration into rocks with different permeability characteristics is performed.

Conclusion

The conducted analysis of the literature demonstrated that one of the principal pathways for fluid leakage

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along the wellbore is the formation of gaps between the cement sheath and the confining surfaces, which may subsequently lead to loss of zonal isolation and deterioration of well performance. In this regard, particular importance should be placed on proper wellbore conditioning and the effective displacement of drilling fluids prior to cementing.

It was established that, when evaluating the compatibility of process fluids, it is necessary to consider not only their macroscopic interactions but also the compatibility of their filtrates. The formation of insoluble precipitates and emulsions in the near-wellbore region can result in pore plugging and a reduction in the permeability of the productive formation.

The analysis further showed that the onset of cement slurry losses is, in most cases, associated with processes occurring during the pre-cementing circulation stage. This finding highlights the need for more rigorous control of drilling fluid properties and hydrodynamic conditions at this critical phase of well construction.

In addition, it was determined that, alongside fluid compatibility and the degree of wellbore and casing cleaning, the key indicators of spacer fluid performance include the stability of rheological properties, an optimized pumping rate, sufficient contact time, and a properly selected spacer fluid volume. Collectively, these factors play a decisive role in ensuring effective completion of productive formations while minimizing formation damage and preserving reservoir permeability.

ADDITIONAL INFORMATION

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