Global Journal of Research in
Engineering and Technology
Journal homepage: https://gsjournals.com/gjret/
ISSN: 2980-4205 (Online)

(REVIEW ARTICLE)

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Next-generation drilling fluids for horizontal and multilateral wells: A conceptual approach

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Global Journal of Research in Engineering and Technology, 2024, 02(02), 011–019

Publication history: Received on 19 August 2024; revis.ed on 01 October 2024; accepted on 04 October 2024

Article DOI: https://doi.org/10.58175/gjret.2024.2.2.0028

Abstract

The development of next-generation drilling fluids is crucial for the success of horizontal and multilateral wells, which pose unique challenges such as torque and drag, hole cleaning difficulties, and wellbore instability. This review explores the evolving role of drilling fluids, focusing on the desired properties required to address these challenges, including enhanced cuttings transport, reduced torque and drag, and improved wellbore stability. Furthermore, the paper discusses innovative additives, such as nanoparticles, high-performance polymers, and biodegradable lubricants, which are key to optimizing fluid performance. Environmental considerations and the chemical and mechanical interactions between fluid components are also analyzed. Finally, the paper examines future trends in drilling technology, highlighting the expected benefits of next-generation fluids and identifying potential challenges for future research and development. These advanced fluids are positioned to revolutionize drilling efficiency while maintaining sustainability in increasingly complex drilling environments.

Keywords: Next-generation drilling fluids; Horizontal wells; Multilateral wells; Torque and drag reduction; Hole cleaning efficiency; Fluid additives

1 Introduction

The evolution of drilling technologies has led to the rise of horizontal and multilateral wells, which have become increasingly essential for maximizing reservoir contact and enhancing production rates. These wells enable operators to tap into larger portions of the reservoir, optimizing recovery and ensuring economic viability, particularly in unconventional and hard-to-reach resources (Gao & Bi, 2022). However, the unique challenges posed by horizontal and multilateral wells, such as increased friction, torque, drag, and difficulty in hole cleaning, require specialized solutions—chief among them being advancements in drilling fluids (Teodoriu & Bello, 2021).

Drilling fluids, also known as drilling muds, play a crucial role in maintaining wellbore stability, cooling the drill bit, and facilitating the removal of cuttings from the well. In horizontal and multilateral wells, the complexity of operations exacerbates issues such as wellbore instability and inadequate cuttings removal, making it critical for drilling fluids to perform beyond their conventional capabilities. Given the complexities of these wells, the industry faces a pressing need to develop next-generation drilling fluids designed specifically to address these challenges (Deville, 2022).

This paper aims to propose and discuss the development of next-generation drilling fluids, focusing on how these fluids can improve hole cleaning efficiency, reduce torque and drag, and enhance overall wellbore stability. The scope will

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include a review of the challenges associated with horizontal and multilateral drilling, the desired properties of next-generation drilling fluids, innovative additives and formulations, and future trends in this domain.

2 Challenges in Horizontal and Multilateral Drilling

2.1 Torque and Drag Issues

One of the primary challenges encountered in horizontal and multilateral drilling is the increased torque and drag on the drill string. Torque refers to the rotational force required to turn the drill string, while drag is the resistance experienced when moving the string in and out of the wellbore (Etaje, Shor, & Lashkari, 2022). These issues become more pronounced as the wellbore deviates from vertical to horizontal, where the contact area between the drill string and the wellbore walls increases. The longer the horizontal section, the greater the frictional forces exerted on the drill string, leading to higher torque and drag (Al-Shargabi et al., 2022).

In multilateral wells, where multiple laterals branch out from a single vertical wellbore, the complexity of the wellbore geometry further exacerbates torque and drag issues. High levels of torque can strain drilling equipment, increasing the likelihood of mechanical failure, while excessive drag can lead to stuck pipe, a situation in which the drill string becomes lodged in the wellbore (Oyedere, 2020). Both issues can significantly impact operational efficiency, causing delays, increasing costs, and in extreme cases, leading to the abandonment of the well. The development of advanced drilling fluids with lubricating properties is critical to reducing the friction between the drill string and the wellbore walls, thereby mitigating torque and drag (Jiang et al., 2022).

2.2 Hole Cleaning Difficulties

Efficient hole cleaning is essential for maintaining wellbore stability and preventing operational issues such as stuck pipe or loss of circulation. In vertical wells, gravity aids in the removal of drill cuttings, as they naturally fall to the bottom of the well and are then transported to the surface by the drilling fluid. However, in horizontal and multilateral wells, the dynamics of hole cleaning are drastically different. In horizontal sections, cuttings tend to settle at the low side of the wellbore due to gravity, making it difficult for the fluid to transport them effectively (Deshmukh & Dewangan, 2022).

Inefficient hole cleaning can lead to the accumulation of cuttings in the wellbore, which increases the risk of blockages, stuck pipe, and wellbore instability. Additionally, excessive cuttings build-up can lead to a condition known as "pack-off," where the annular space between the drill string and the wellbore becomes packed with cuttings, preventing fluid circulation and hindering further drilling progres (Erge & van Oort, 2020) s. This situation is particularly problematic in extended-reach and multilateral wells, where the horizontal sections can stretch for thousands of meters (Alawami, Bassam, Gharbi, & Al Rubaii, 2020).

To address this challenge, drilling fluids must be designed with enhanced carrying capacity and suspension properties. Rheological properties such as yield point, plastic viscosity, and gel strength must be optimized to ensure the fluid can lift and transport cuttings effectively, even in long horizontal sections. Moreover, high-performance fluids that can maintain their properties under varying downhole conditions are essential for successful hole cleaning in complex wellbore geometries (Alawami et al., 2020).

2.3 Wellbore Instability Concerns

Wellbore instability is another critical challenge in horizontal and multilateral drilling, often exacerbated by the longer exposure time of the wellbore to drilling fluids and the increased surface area of contact. Instability can manifest in various ways, including wellbore collapse, shale swelling, and excessive fluid loss into the formation. These issues can compromise well integrity, increase non-productive time (NPT), and lead to costly remedial operations (Yan, Kang, & You, 2020).

One of the primary causes of wellbore instability is the interaction between the drilling fluid and the surrounding formation. In formations prone to swelling, such as shales, contact with water-based drilling fluids can cause the rock to absorb water, swell, and eventually collapse, leading to stuck pipe or lost circulation. In multilateral wells, where the wellbore branches into multiple laterals, the risk of instability is further heightened due to the increased complexity of the wellbore geometry (Ibrahim, 2021).

Maintaining wellbore stability requires drilling fluids with tailored rheological and chemical properties. Fluids must provide sufficient support to the wellbore walls to prevent collapse while also minimizing fluid loss into the formation

(Abdullah et al., 2022). Inhibitive drilling fluids, designed to prevent swelling and degradation of sensitive formations, are often necessary for maintaining wellbore integrity. The ability of next-generation fluids to stabilize the wellbore over extended periods is crucial for the success of horizontal and multilateral drilling operations (Jingen, Egwu, & Xionghu, 2022).

2.4 Current Limitations of Conventional Drilling Fluids

While effective for vertical wells, conventional drilling fluids often fall short of the performance required for horizontal and multilateral wells. These fluids are typically formulated for vertical wellbore geometries, where the primary concern is vertical cuttings transport and basic wellbore stabilization. However, the complexities introduced by horizontal and multilateral drilling demand more advanced fluid formulations (Oseh et al., 2020). One of the key limitations of conventional fluids is their inability to efficiently transport cuttings in horizontal sections. As previously discussed, settling cuttings in the lower part of the wellbore is a significant issue in horizontal drilling, and conventional fluids may lack the necessary suspension and carrying capacity to address this. Additionally, conventional fluids often have limited lubricating properties, making them less effective at reducing torque and drag in deviated wellbores (Teodoriu & Bello, 2021).

Another limitation is the stability of conventional fluids under high-pressure, high-temperature (HPHT) conditions, which are common in deep and extended-reach wells. Many traditional fluids begin to degrade or lose their rheological properties under such conditions, leading to wellbore instability, fluid loss, or equipment failure. Therefore, next-generation drilling fluids must be designed to withstand extreme downhole conditions without compromising performance (Bashir, Piaskowy, & Alusta, 2021).

Moreover, environmental concerns associated with conventional drilling fluids, particularly oil-based muds (OBMs), pose additional challenges. OBMs are often more effective than water-based muds (WBMs) in terms of lubricity and wellbore stability but are associated with higher environmental risks. Disposal of OBMs is tightly regulated, and their use can significantly increase operational costs. Developing environmentally friendly alternatives that do not sacrifice performance is a key area of focus for next-generation fluid research (Njuguna et al., 2022).

3 Desired Properties of Next-Generation Drilling Fluids

3.1 Enhanced Hole Cleaning Efficiency

One of the most critical functions of drilling fluids is to remove cuttings from the wellbore during the drilling process. In vertical wells, gravity assists in the removal of cuttings, allowing them to be easily transported to the surface by the circulating fluid. However, in horizontal and multilateral wells, where the wellbore deviates from vertical, gravity causes cuttings to settle on the low side of the wellbore, making their removal far more difficult (Al-Shargabi et al., 2023).

Effective hole cleaning is particularly important in horizontal sections, as the accumulation of cuttings can lead to serious operational issues such as stuck pipe, reduced drilling efficiency, and even wellbore instability. To address these challenges, next-generation drilling fluids must be engineered with superior carrying capacity and suspension properties (Abbas, Alsaba, & Al Dushaishi, 2022).

Rheological properties like yield point, gel strength, and plastic viscosity play a crucial role in cuttings transport. The fluid must maintain sufficient yield point to suspend cuttings when circulation is stopped and exhibit the right level of gel strength to keep cuttings from settling during drilling pauses. Enhanced hole cleaning efficiency requires a careful balance between these properties to ensure that cuttings are effectively removed from the wellbore, particularly in long, extended-reach horizontal sections (Gåseland Bekkevik, 2022).

Additionally, the flow velocity of the drilling fluid should be high enough to prevent the formation of cuttings beds along the horizontal portion of the well. Properly designed next-generation fluids can help eliminate or significantly reduce the risk of pack-off, where cuttings obstruct fluid flow and impede the drill string. This enhanced hole cleaning capability will be critical for maintaining wellbore integrity and ensuring smooth drilling operations (Al-Shargabi et al., 2023).

3.2 Reduction of Torque and Drag

Torque and drag are common issues in horizontal and multilateral drilling, arising from the friction between the drill string and the wellbore walls. In vertical wells, the effects of torque and drag are less pronounced, but as the wellbore becomes more deviated, the contact area between the drill string and the wellbore increases, causing greater frictional forces. These forces result in higher torque, which requires more rotational force to turn the drill string, and drag, which makes it more difficult to move the drill string in and out of the well (Etaje et al., 2022).

Excessive torque and drag can lead to numerous operational problems, including stuck pipe, mechanical wear on equipment, and reduced drilling efficiency. Next-generation drilling fluids should be designed to mitigate these risks with enhanced lubricating properties that minimize friction between the drill string and the wellbore. This friction reduction can be achieved by incorporating specialized lubricants or friction-reducing additives in the fluid formulation (Ohia et al., 2021).

Synthetic lubricants, for example, can provide superior friction reduction compared to conventional water-based fluids. These additives form a thin film between the drill string and the wellbore, allowing for smoother rotation and movement of the string. Additionally, biodegradable and environmentally friendly lubricants are gaining popularity, as they offer similar friction-reducing benefits while reducing the environmental impact of drilling operations. By reducing torque and drag, next-generation drilling fluids will help extend the life of drilling equipment, improve operational efficiency, and lower the overall cost of drilling (Rahman et al., 2021).

3.3 Improved Rheological Properties for Stability

Wellbore stability is a key concern in horizontal and multilateral drilling, as the increased surface area of contact between the wellbore and the surrounding formation amplifies the risk of instability. Wellbore collapse, excessive fluid loss, and formation damage are all potential hazards that can arise from inadequate support provided by the drilling fluid. Therefore, next-generation drilling fluids must be designed with improved rheological properties to maintain wellbore stability under a variety of challenging conditions (Xu, Cao, Dong, & Yan, 2023).

Rheology refers to the flow behavior of the fluid, and it is determined by factors such as viscosity, yield stress, and gel strength. In horizontal and multilateral wells, the drilling fluid must exhibit the right balance of these properties to prevent the collapse of the wellbore, particularly in weak or fractured formations. A higher viscosity is often required to provide support to the wellbore walls, while maintaining adequate flow properties to facilitate the removal of cuttings (Chen et al., 2022).

Additionally, next-generation fluids must be stable under extreme downhole conditions, such as high pressure and temperature (HPHT) environments. Many conventional drilling fluids lose their viscosity and other critical properties when exposed to HPHT conditions, leading to wellbore instability and other operational issues. Advanced fluid formulations, incorporating high-performance polymers or nanoparticles, can help ensure that the fluid retains its rheological properties under such conditions, thereby maintaining wellbore stability and minimizing the risk of collapse (Marhoon, 2020). Furthermore, the fluid's ability to prevent fluid loss into the formation, known as fluid loss control, is a critical component of wellbore stability. Next-generation fluids must exhibit low fluid loss characteristics to prevent the formation from absorbing large amounts of fluid, which can weaken the wellbore and lead to formation damage or collapse (Mao et al., 2022).

3.4 Compatibility with Advanced Drilling Techniques

Modern drilling operations increasingly rely on advanced techniques such as managed pressure drilling (MPD), underbalanced drilling (UBD), and extended-reach drilling (ERD) to optimize wellbore performance and manage downhole pressures (Marhoon, 2020). These techniques place additional demands on drilling fluids, requiring them to perform well under a range of pressure and flow conditions while maintaining their rheological properties (Ezeh, Ogbu, Ikevuje, & George, 2024; Ochulor, Sofoluwe, Ukato, & Jambol, 2024). For instance, MPD involves carefully controlling the pressure profile in the wellbore to prevent blowouts or lost circulation. The drilling fluid must work in conjunction with advanced surface equipment to manage downhole pressure in real-time, necessitating a fluid that can adapt to fluctuating pressure conditions without compromising stability or hole cleaning performance. Similarly, in UBD operations, the wellbore is maintained at a pressure lower than the formation pressure to minimize formation damage and improve production. This requires fluids that maintain stable flow and transport cuttings even under lower pressure conditions (UlHaque, Saboor, Bouarfetine, Hammoudi, & Serhane, 2020).

Next-generation drilling fluids must be compatible with these advanced techniques, exhibiting the flexibility and performance necessary to support a variety of operational scenarios. Furthermore, fluids must be designed to integrate with real-time monitoring systems, allowing for dynamic adjustments to fluid properties based on changing downhole conditions. This compatibility with advanced drilling technologies will be essential for optimizing wellbore performance and ensuring the success of horizontal and multilateral wells (Teodoriu & Bello, 2021).

4 Innovative Additives and Formulations

4.1 Potential Fluid Additives for Enhanced Performance

Additives play a critical role in enhancing the functionality of drilling fluids, especially for horizontal and multilateral wells. The primary goal of fluid additives is to improve the fluid's ability to perform under challenging downhole conditions, such as high temperatures, high pressures, and extended-reach drilling, while addressing specific issues like torque and drag reduction, cuttings suspension, and wellbore stability. Several innovative additives are being researched and implemented to optimize next-generation drilling fluids (Jambol, Ukato, Ozowe, & Babayeju, 2024; Ogbu, Ozowe, & Ikevuje, 2024).

Nanoparticles: Nanotechnology has emerged as a promising solution for enhancing the performance of drilling fluids. Nanoparticles can be used to improve the thermal stability, lubricity, and filtration properties of the fluid. Their small size allows them to interact effectively with the formation and fluid components, creating a thin, uniform film that reduces friction between the drill string and wellbore. Additionally, nanoparticles can improve cuttings transport and enhance the fluid's ability to seal microfractures, minimizing fluid loss into the formation (Cheraghian, 2021).

Lubricants: Advanced lubricants are essential for reducing torque and drag in horizontal and multilateral wells. These additives work by decreasing the friction between the drill string and the wellbore, allowing smoother movement of the drill string and reducing wear on equipment. Synthetic lubricants, such as ester-based or silicone-based fluids, have provided excellent lubricity under harsh drilling conditions. Furthermore, biodegradable lubricants are gaining popularity due to their minimal environmental impact, making them a preferred choice for operators focused on sustainability (Medhi et al., 2024).

High-Performance Polymers: Polymers are often added to drilling fluids to enhance their viscosity, gel strength, and fluid loss control properties. In next-generation fluids, high-performance polymers such as xanthan gum, polyacrylamides, and starch-based additives can improve cuttings suspension and prevent the settling of cuttings in horizontal sections. These polymers form a flexible network within the fluid, allowing it to maintain its flow properties while effectively suspending cuttings. Moreover, some polymers can help seal permeable formations, reducing fluid loss and enhancing wellbore stability (Karakosta, Mitropoulos, & Kyzas, 2021).

Fluid Loss Control Agents: Effective fluid loss control is essential for maintaining wellbore integrity, especially in fractured or highly permeable formations. Next-generation drilling fluids incorporate advanced fluid loss control agents such as microparticulate materials, asphaltic compounds, and synthetic fibers. These additives work by creating a low-permeability filter cake on the wellbore walls, preventing the drilling fluid from penetrating the formation. These agents help maintain wellbore stability, reduce formation damage, and improve overall drilling performance by minimizing fluid loss (Ahmed & Salehi, 2021).

4.2 Chemical and Mechanical Interactions in Next-Gen Fluids

The performance of next-generation drilling fluids is not only determined by the individual properties of additives but also by the chemical and mechanical interactions between different fluid components. Understanding these interactions is key to optimizing fluid formulations for specific drilling applications.

Rheological Synergy: The rheological properties of drilling fluids, such as viscosity, yield point, and gel strength, are influenced by the interactions between polymers, particulates, and other additives. In next-generation formulations, achieving a balance between these properties is crucial for ensuring efficient cuttings transport, hole cleaning, and wellbore stability. For instance, polymers and nanoparticles can interact synergistically to enhance fluid viscosity and suspension properties without excessively increasing pump pressure. This allows for better flow control and reduces the risk of stuck pipe in horizontal and multilateral wells (Mohamed, Salehi, & Ahmed, 2021).

Frictional Interactions: The mechanical interaction between drilling fluids and the wellbore is critical in determining fluid performance. Additives like lubricants and nanoparticles reduce frictional forces by forming a protective film on the wellbore surface, reducing torque and drag. However, this reduction in friction must be carefully controlled to avoid excessive fluid lubricity, which could lead to problems such as casing wear or tool failure. Therefore, next-generation formulations must account for the additives' chemical composition and their mechanical behavior under different drilling conditions (Abdullah et al., 2022).

Thermal Stability and Chemical Compatibility: Horizontal and multilateral wells often encounter high-pressure, high-temperature (HPHT) environments, which can degrade conventional drilling fluids. Next-generation fluids must be thermally stable and chemically compatible with the formation and drilling environment. For example, certain polymers and nanoparticles must be selected for their resistance to temperature degradation, ensuring that the fluid retains its properties throughout the drilling process. Moreover, compatibility with the geological formation is crucial to avoid chemical reactions that could lead to formation damage or wellbore instability (Martin, 2022).

4.3 Environmental Considerations in Fluid Development

As the oil and gas industry increasingly emphasizes sustainability, the development of next-generation drilling fluids must incorporate environmental considerations. Traditional drilling fluids, particularly those based on oil or synthetic materials, can pose significant risks to the environment through contamination, toxicity, and improper disposal. Therefore, next-generation fluids must be designed to reduce environmental impact (Ogbu, Iwe, Ozowe, & Ikevuje, 2024; Onita & Ochulor, 2024; Ukato, Jambol, Ozowe, & Babayeju, 2024).

One of the key strategies for minimizing environmental harm is the use of biodegradable additives. Biodegradable lubricants, polymers, and fluid loss agents decompose naturally over time, reducing the risk of long-term contamination. These environmentally friendly alternatives can perform on par with conventional additives while offering the advantage of lower toxicity and reduced environmental persistence. For example, bio-based lubricants derived from plant oils are increasingly used to reduce drilling operations' environmental footprint (Yin & Yang, 2020).

Another important trend in environmentally conscious fluid development is the shift toward water-based drilling fluids (WBM). These fluids are generally less toxic than oil-based or synthetic-based fluids and are easier to dispose of after use. However, WBMs often face challenges in terms of performance, particularly in high-temperature environments or when dealing with complex wellbore geometries. Next-generation WBMs are being developed with enhanced additives such as high-performance polymers and nanoparticles to overcome these limitations, offering improved thermal stability and lubricity while maintaining low environmental impact (Pichler et al., 2023).

In addition to developing more eco-friendly fluid formulations, the industry is also focusing on recycling and reusing drilling fluids to reduce waste. Advanced treatment technologies allow for the reclamation and reuse of fluids from previous wells, minimizing the need for fresh water or new fluid production. Proper waste management practices, including the treatment and safe disposal of drilling fluids, further contribute to reducing the environmental impact of drilling operations. This approach benefits the environment and reduces operational costs by lowering the demand for new materials (Tabatabaei, Kazemzadeh, Sabah, & Wood, 2022).

5 Conclusion and Future Trends

The ongoing advancements in drilling technology, particularly in horizontal and multilateral wells, are reshaping the requirements for drilling fluids. Technologies like extended-reach drilling, managed pressure drilling (MPD), and rotary steerable systems (RSS) demand fluids that can adapt to more complex wellbore geometries, deeper wells, and higher-pressure environments. As these technologies push the limits of what is technically feasible, drilling fluids must keep pace by offering enhanced performance and durability.

One of the key areas of focus is the development of fluids that can withstand the high pressures and temperatures associated with deep wells while maintaining effective cuttings transport and wellbore stability. Fluid designers are also exploring using smart fluids, which are engineered to respond to specific downhole conditions such as temperature, pressure, or formation type. These fluids can adjust their rheological properties in real time, improving drilling efficiency and reducing the likelihood of wellbore instability.

Next-generation drilling fluids are expected to deliver significant benefits in horizontal and multilateral drilling, addressing many of the challenges currently faced by operators. One of the most anticipated improvements is enhanced hole cleaning efficiency. In horizontal wells, maintaining an effective flow of cuttings to the surface is critical, and next-gen fluids are being designed to optimize cuttings transport even in extended-reach scenarios. This leads to more stable wellbores, reduced risk of stuck pipe, and improved overall drilling performance.

Another key benefit is the reduction of torque and drag. As drill strings encounter friction while navigating through complex wellbore paths, fluid additives like advanced lubricants and nanoparticles can help minimize these forces. This reduction in torque and drag improves drilling efficiency and extends the life of drilling equipment, reducing maintenance costs and downtime. Additionally, next-generation fluids are being formulated to improve wellbore stability, particularly in challenging geological formations. Enhanced fluid loss control agents and advanced rheological properties help create a more stable drilling environment, reducing the likelihood of costly wellbore collapse or formation damage.

Despite the promising advances, the development of next-generation drilling fluids still faces several challenges that warrant further research and innovation. One of the main challenges is the need to balance fluid performance with environmental sustainability. While many next-gen fluids incorporate biodegradable and non-toxic additives, ensuring that these fluids can perform effectively in extreme drilling conditions without compromising environmental safety remains a complex task.

Moreover, as drilling environments become more demanding, the need for fluids that can perform under high-pressure, high-temperature (HPHT) conditions is increasing. Developing fluids that can retain their properties in these extreme environments while maintaining cuttings suspension and wellbore stability presents an ongoing challenge. There are also opportunities for integrating digital technologies, such as machine learning and real-time data analytics, into fluid design and management. These technologies could enable more precise monitoring and optimization of fluid performance, allowing operators to adapt fluids dynamically to changing downhole conditions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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